VOL. 15 No. 10, p.p. 265-296 APRIL 1954

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

A COLD CATHODE GAS-DISCHARGE TUBE AS A SWITCHING ELEMENT IN AUTOMATIC TELEPHONY

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621.318.57: 621.395.34

*The idea of replacing electro-mechanical contact devices in automatic telephone exchanges by electronic ones, is anything but new. In patent literature throughout the last few decades, a number of such proposals can be found, involving the application of photocells, cathode-ray tubes or other special vacuum tubes, transistors, gas-discharge tubes, etc. Vacuum tubes specially designed for use as switching elements in telephony were described in this Review some years ago *). In the following article a gas-discharge tube for the same purpose will be discussed. By means of this tube it is possible to built up the relay, selector and other circuits used in automatic telephony.*

Electro-magnetic switches are used on a large scale in automatic telephony for establishing and breaking connections — both line connections between subscribers, and connections between a variety of auxiliary equipment (for selecting, ringing current, busy-tone, call registration, etc.). A certain mechanical delay is always associated with such switching devices (relays, selectors) due to their inertia. The same applies to the controlling devices, which determine the positions of the switches. In modern installations, not every selector has its own controlling devices, but these are available centrally and cover a number of lines. The smaller the inertia of these control devices, the sooner they are again available for another subscriber and the fewer of them are required. For a considerable time, attempts have been made to develop electronic devices — which are practically inertia-free — for control devices and for other purposes.

A second and fundamental advantage of electronic switching devices is that unlike relays, they require no maintenance. Present developments in electrical engineering offer, in principle, a number of ways of achieving electronic switching. In this article we shall confine ourselves to one of these possibilities, viz. the use of cold-cathode gas-discharge tubes, which have been developed in the Philips Research Laboratory at Eindhoven. After a description of the tubes, we shall discuss a number of circuits in which they can be applied. Several of these circuits have been incorporated in an experimental all-electronic telephone exchange [1]).

The cold cathode gas-discharge tube

The tube in question is made in two versions, type Z 500 T and Z 501 T (*fig. 1*). Each contains a cathode and an anode but the former contains, in addition, one trigger electrode, and the latter two trigger electrodes, which serve to initiate the discharge. The tubes are filled with argon.

The discharge is a glow-discharge which spreads over the cathode according to the current intensity. At a current of 6 mA the cathode is completely covered by the discharge.

The cathode consists of a small nickel plate coated with a layer of activated barium oxide. The barium oxide is activated by partly decomposing it, by passing current pulses through the tube (a *getter* binding the oxygen released), until the lowest possible working voltage is obtained. The tubular-shaped anode and the wire trigger electrode(s) are also made of nickel and are mounted parallel to the cathode. The tube has been so designed that the greatest possible difference is

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*) J. L. H. Jonker and Z. van Gelder, Philips tech. Rev. **13**, 49-54 and 82-89, 1951.

[1]) See also W. Six, Communication News **14**, 58-69, 1954 (No. 2).

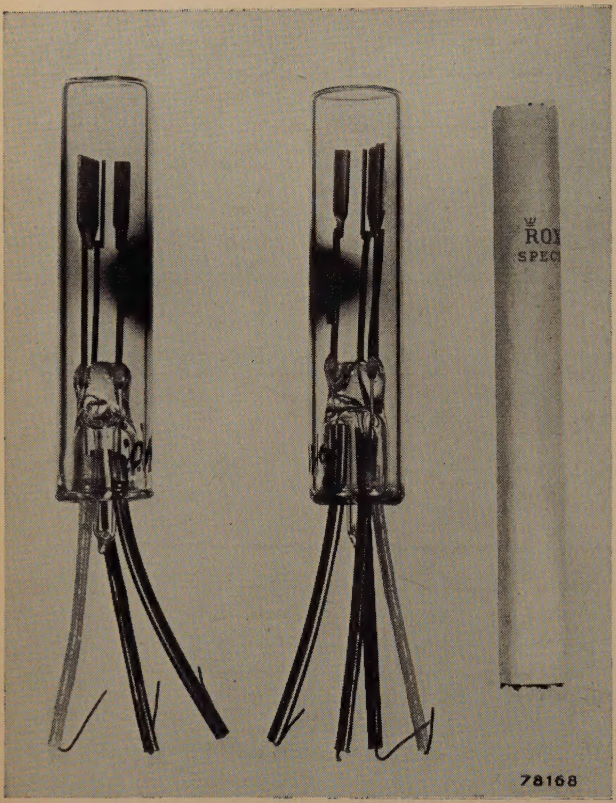

Fig. 1. Cold-cathode gas-discharge tubes with oxide-coated cathodes. Left, type Z 500 T with one trigger electrode. Right, type Z 501 T with two trigger electrodes. The tubes are without bases, and connections are soldered direct to the lead-in wires. Diameter 12 mm, length approx. 55 mm.

obtained between the breakdown voltage and the cathode-anode working voltage; thus the permissible tolerances of supply voltages, resistance values, etc. are fairly wide.

For a given gas, the breakdown voltage is determined by the product of the density p of the gas and the electrode distance d, according to the Paschen curve (*fig. 2*). The working voltage, on the other hand, depends very little on pd, as long as pd does not exceed a value at which *anode fall* occurs — a state which is undesirable anyway, due to the risk of relaxation oscillations. The values p and d have therefore been so chosen that pd is situated a good deal to the right of the minimum in the Paschen curve, though not so far that an anode fall can occur. The breakdown voltage ($V_{\text{ign}\,a}$) is then 175 V or higher. Owing to the oxide-cathode, the running voltage is kept down to approximately 60 V.

The trigger electrode is at a distance $d' < d$ from the cathode, such that pd' corresponds to the minimum in the Paschen curve. The ignition voltage of the trigger electrode has thus the lowest possible value, viz. 65-78 V.

Once a discharge has been initiated via the trigger electrode, the presence of ions and electrons in the tube reduces the breakdown voltage $V_{\text{ign}\,a}$ of the anode by an amount depending on the current i_a' flowing through the trigger electrode (*fig. 3*).

Fig. 3 shows that $V_{\text{ign}\,a} = 160$ V at $i_a' = 30$ μA. Thus, if a direct voltage of 160 V is applied between anode and cathode, the tube will ignite only if the trigger electrode current is at least 30 μA. A current pulse of only short duration is sufficient for this, since the main discharge can be initiated within an interval of 10^{-4}-10^{-5} sec. Once initiated, the discharge continues, even if the current i_a' drops to zero. It is therefore possible to supply i_a' from a capacitor, as shown in *fig. 4*: as soon as any current passes through the trigger electrode, this current will temporarily assume a high value, since the capacitor is then discharged via a circuit having only a low resistance. If a positive bias voltage is employed on the trigger electrode, only a low ignition voltage is required to fire the tube.

As mentioned above, the tube type Z 501 T is provided with two trigger electrodes. It will later be demonstrated that this is of special advantage for tubes intended for service as selector switches.

Since the tube has no filament, it generates heat only during actual operation, and even then at the rate of no more than a fraction of a watt and, as a rule, for short periods only. There are, therefore, two advantages compared to thermionic-emission tubes: low power consumption, and the absence of any cooling problems (particularly important in compact installations with a large number of tubes).

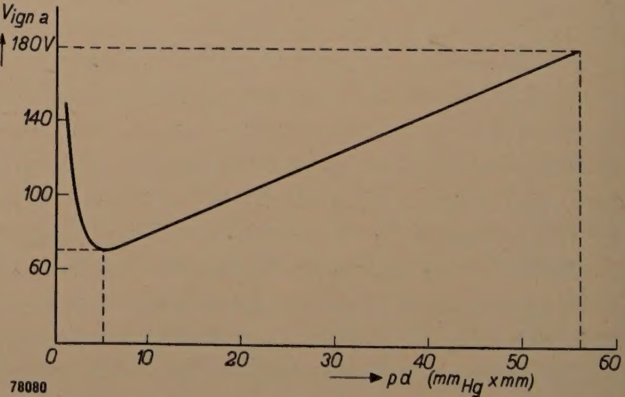

Fig. 2. The Paschen curve (ignition voltage $V_{\text{ign}\,a}$ as a function of the product of gas density p and electrode distance d), for argon, with an oxide-coated cathode.

As a third advantage we might add that these tubes have a very long life. A working life ("nett" life) averaging 12 000 hours at a current of 6 mA can be attained, and, according to prevailing standards, a life of 6000 hours can be expected for normal production-line tubes. Since the majority of the tubes in the circuits to be discussed presently, are only operating for a fraction of the time, this means that these tubes will have a "gross" life of centuries. At currents lower than 6 mA, the life of these tubes is inversely proportional to the current; at currents higher than 6 mA, their life is inversely proportional to rather more than the cube of thecurrent ²).

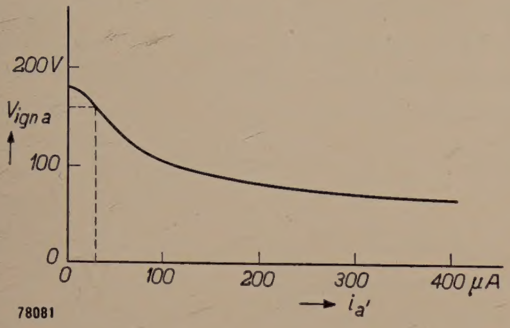

Fig. 3. Ignition voltage $V_{ign\,a}$ of the tube Z 500 T as a function of the trigger electrode current i'_a.

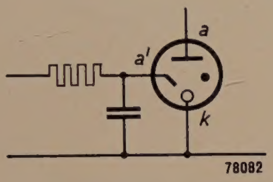

Fig. 4. A circuit for igniting tube Z 500 T (with anode *a*, cold cathode *k* and trigger electrode *a'*; the dot indicates the gas filling). As soon as the capacitor is charged up to the ignition voltage of *a'* (65 to 78 V), it discharges across *k-a'* with a fairly large current, which initiates the main anode current *k-a*.

Circuits for the cold-cathode tube

On ignition, the voltage between anode and cathode drops from the initial value V_{ak} — which, in order to avoid spontaneous ignition, should be below 175 V — to the working voltage (approx. 60 V). The difference V_{ak} — 60 V is then developed across a resistor in series with the tube and can, in turn, be used for firing another tube.

It has already been mentioned that the trigger electrode cannot serve for extinguishing a tube already ignited. The question is, how can this be accomplished? In some cases there is no objection against a short interruption of the anode circuit. In other cases the supply voltage can be periodically reduced to below the working voltage, so that the discharge is terminated; this may be effected by a supply voltage composed of a direct voltage of 100 V, upon which an alternating voltage of amplitude 60 V has been superimposed. The discharge can, furthermore, be extinguished by reducing the tube voltage to below the working voltage by means of a pulse: either a negative pulse to the anode, or a positive pulse to the cathode. Still another possibility is to arrange the circuit in such a way that it functions as an oscillator as long as the potential of the trigger electrode is high enough; when the potential applied to the trigger electrode is brought down, the oscillation stops.

Examples of these various possibilities will be encountered in the circuits to be dealt with below. As a practical test and also for demonstration purposes, several of these circuits have been applied in an experimental automatic telephone exchange for ten lines (*fig.* 5), which has already been functioning for some years in the Philips Research Laboratory in Eindhoven. Neither mechanical switches nor relays are to be found in this fully electronic exchange; the tubes employed, apart from three thermionic amplifying tubes (ECC 81), are exclusively cold-cathode tubes of the types Z 500 T and Z 501 T.

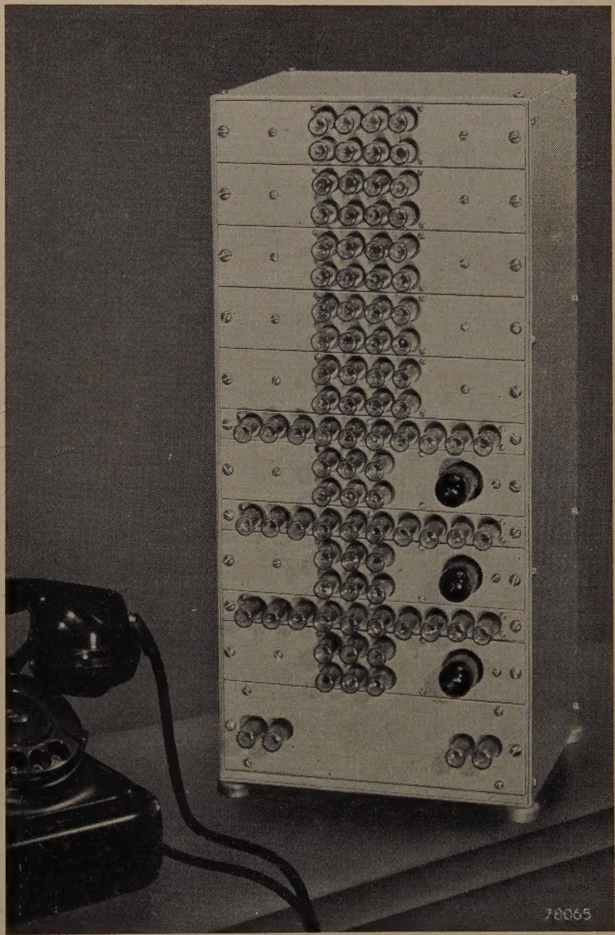

Fig. 5. Fully-electronic telephone exchange for 10 lines, in use in the Philips Research Laboratory in Eindhoven. This exchange contains 62 cold-cathode tubes Z 500 T, 30 cold-cathode tubes Z 501 T, and 3 double-triodes ECC 81. The power is supplied by two D.C. power packs having potentials of +160 V and —60 V with respect to earth.

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²) G. H. Rockwood, Current rating and life of cold cathode tubes, Trans. Amer. Inst. El. Engrs. **60**, 901-903, 1941.

Relay circuits

Fig. 6a shows a cold-cathode tube, connected in series with an anode resistor R_a and a cathode resistor R_k, to a 160 V source of direct voltage. A voltage divider r_1-r_2 is conneted between the positive terminal and the cathode. It is assumed that $R_a = R_k$, and that $r_1 + r_2 \gg R_k$, so that, if no current passes through the tube, the cathode potential is practically zero. The ratio r_1:r_2 has been so chosen that the tapping point *1* has a potential of +60 V.

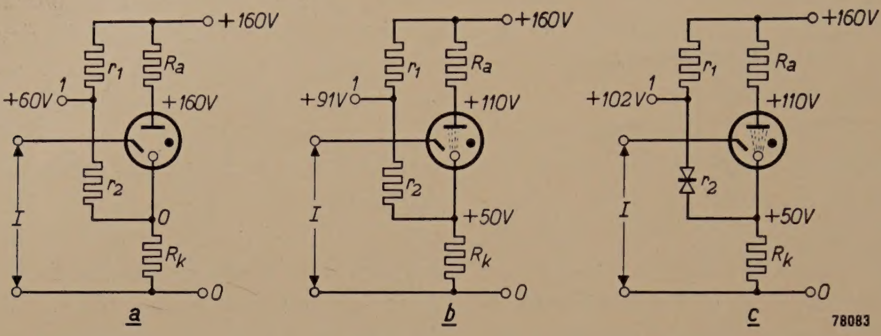

Fig. 6. The cold-cathode tube used as a relay.
a) The tube is not conducting. Point *1* on the voltage divider r_1-r_2 is at a potential of 60 V.
b) The tube has been ignited via the input terminals *I*. The potential at *1* increases to 91 V.
c) By using a varistor for r_2, the potential of *1* can be raised even higher, up to 102 V.
The resistances of r_1 and r_2 are assumed to be high compared to the values of R_a and R_k (= R_a).

When the tube is burning, the voltage between anode and cathode drops from 160 V to 60 V, and the difference of 100 V is equally divided between R_a and R_k. It can be readily verified that the point *1* will then assume a potential of approximately + 91 V (fig. 6*b*). The voltage surge at *1*, from 60 V to 91 V, can be used for igniting or extinguishing another tube.

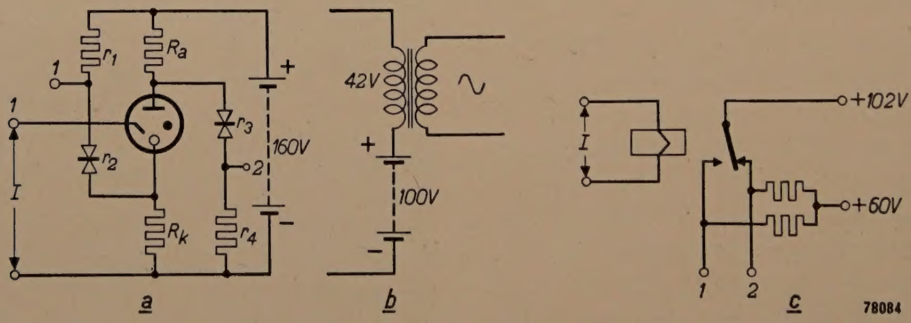

Fig. 7. *a*) Extension of the circuit of fig. 6*c* by a branch r_3 (varistor) - r_4. Tube non-conducting: point *1* at 60 V, point *2* at 102 V. Tube ignited: point *1* at 102 V, point *2* at 60 V.
b) Automatic extinguishing of the tube can be effected by using a supply of 42 V r.m.s. alternating voltage superimposed on a 100 V direct voltage.
c) Relay with a change-over contact *1-2*, of which (*a*) is the electronic equivalent.

This voltage surge can be somewhat increased by using for r_2 a "varistor" (fig. 6*c*), i.e. a resistor whose resistance increases at decreasing voltage. In this way point *1* can be given a potential of +102 V after the tube has been ignited.

These principles have been applied in the relay circuit shown in *fig. 7a*. As long as the tube does not pass a current, point *1* has a potential of +60 V and point *2* a potential of +102 V; after the tube has ignited, point *1* has a potential of +102 V and point *2* a potentials of +60 V. Ignition thus result in the potentials of points *1* and *2* being reversed; in this respect the circuit is equivalent to a relay with a change-over contact (fig. 7*c*). Automatic quenching of the discharge can be effected by supplying the circuit with a pulsating direct voltage dropping periodically below the working voltage (fig. 7*b*) as described above.

It has been demonstrated by Ingram[3]) that by combining gas-discharge tubes and rectifier elements, an equivalent for every relay circuit can be found. *Fig. 8* shows some examples of equivalent switching circuits: *a*) two make-contacts in series, *b*) two make-contacts in parallel, *c*) a make-contact and a break-contact in series, *d*) a make-contact and a break-contact in parallel and a make-contact in series with the two. Explanations of these circuits are given below the figure.

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[3]) S. B. Ingram, Cold-cathode gas-filled tubes as circuit elements, Trans. Amer. Inst. El. Engrs. **58**, 342-346, 1939.

Counting circuit

Decade pulse-counting circuits can also be built up with cold-cathode tubes. It will later be demonstrated how such counting circuits can be applied in automatic telephony, but for the time being, only counting in a general sense will be considered. A counting circuit is shown in *fig. 9*. The pulses to be counted, which must be of approx. 30 V amplitude, are applied, with positive polarity, via the input terminal *I* and the capacitors C_1, to the trigger electrode of the ten tubes *1*, *2*, ... *0* of the first decade (D_1). In the initial position, only the trigger electrode of tube *1* has a bias (+60 V), derived from a voltage divider R_3-R_4 across the 160 V supply voltage. As a consequence, the first pulse will ignite only tube *1*, whose cathode potential will then rise from 0 to approx. 100 V, bringing the potential of the trigger electrode of tube *2* to the same

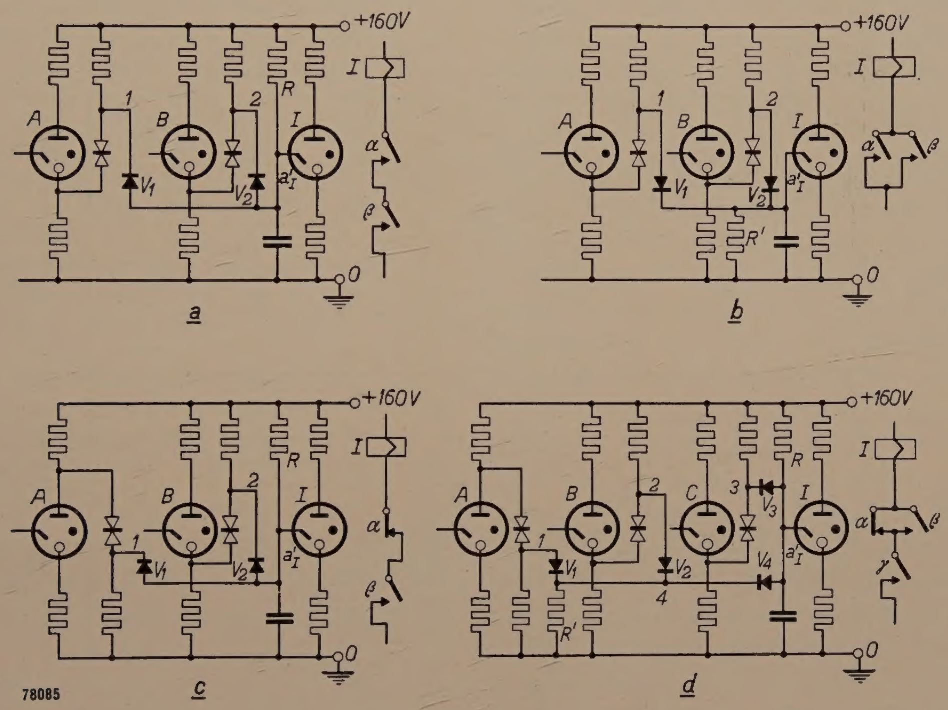

Fig. 8. Various relay circuits with cold-cathode tubes (derivatives of fig. 7*a*). Whether tube *I* ignites depends on the condition of tubes *A* and *B* and *C*, in a manner analogous to the energizing of the adjacent relay *I*, which depends on the position of the contacts *α* and *β* and *γ*.

The resistance of *R* is large compared to the reverse resistance of the rectifier elements, and that of *R'* (in *b* and *d*) is low compared to *R*. The capacitor between the trigger electrode of *I* and earth, is the trigger condenser mentioned in fig. 4.

Further particulars can be found in the adjacent table (except that for circuit *d*, not all possibilities are given). 0 signifies non-conduction, and × conduction, of a tube or rectifier.

Circuit	Tubes			Potential at point (volts)				Rectifier elements				Potential a'_I (volts)	Tube I
	A	*B*	*C*	*1*	*2*	*3*	*4*	V_1	V_2	V_3	V_4		
a	0	0		60	60			×	×			60	0
	×	0		100	60			0	×			60	0
	0	×		60	100			×	0			60	0
	×	×		100	100			×	×			100	×
b	0	0		60	60			×	×			60	0
	×	0		100	60			×	0			100	×
	0	×		60	100			0	×			100	×
	×	×		100	100			×	×			100	×
c	0	0		100	60			0	×			60	0
	×	0		60	60			×	×			60	0
	0	×		100	100			×	×			100	×
	×	×		60	100			×	0			60	0
d	0	0	0	100	60	60	100	×	0	×	0	60	0
	0	0	×	100	60	100	100	×	0	×	×	100	×
	0	×	×	100	100	100	100	×	×	×	×	100	×
	×	0	×	60	60	100	60	×	×	0	×	60	0
	×	×	×	60	100	100	100	0	×	×	×	100	×
	etc.												

potential. After the ignition of tube *1*, a current passes through the cathode resistor R_1 of tube *1* and through the resistor R_2, common to all the ten tubes. This results in a voltage drop of 40 V across R_2, so that the cathode potential of the nine non-conducting tubes becomes 40 V. The trigger electrode of tube *2* thus assumes a bias of $100 - 40 = 60$ V with respect to the cathode. The second pulse will therefore ignite tube *2*. The cathode potential of this tube then jumps from 40 to 100 V, which causes a charging current through the capacitor C_2 connecting the cathodes of tubes *1* and *2*. Part of this charging current flows through the cathode resistor R_1 of tube *1*, thus temporarily raising the latter's cathode potential to such an amount that this tube is extinguished (an example of quenching by a positive pulse applied to the cathode).

After the second pulse, the state of the circuit is as follows: only tube *2* is burning; its cathode potential is +100 V, while that of all other tubes is +40 V; the trigger electrode of tube *1* has a bias of $60 - 40 = 20$ V (which is insufficient to allow firing of tube *1* by a subsequent pulse); the trigger electrode of tube *3*, however, has a bias of $100 - 40 = 60$ V, while the remaining trigger electrodes have no bias at all. The third pulse will therefore ignite tube *3* only (and in doing so extinguish tube *2*), and so the process will continue.

For counting beyond 10, so that the eleventh pulse will again ignite tube *1*, etc., a connection similar to those between the other tubes is required between tube *0* and tube *1*. For this, however, a rectifier element (*V*) is required, connected so that its conduction direction is from point *b* to point *a*. This is essential in order to prevent point *a* from assuming the potential of point *b* (zero) when all tubes are non-conducting (the resistances of R_1 and R_2 are considerably smaller than those of R_3 and R_4); if this happened the trigger electrode of tube *1* would lose its bias. On firing, the cathode potential of tube *0* jumps from 40 to 100 V, and part of this voltage surge is fed to point *a* via the rectifier element. From here, it can be fed to a second decade (D_{10}) for counting the tens. At the tenth pulse therefore, not only tube *0* of D_1, but also tube *1* of D_{10} will fire. A third decade (D_{100}) can be connected for counting the hundreds, and so on.

Since the discharge in the tubes is visible as a violet light, the number of pulses counted can be directly read if the tubes are provided with figures.

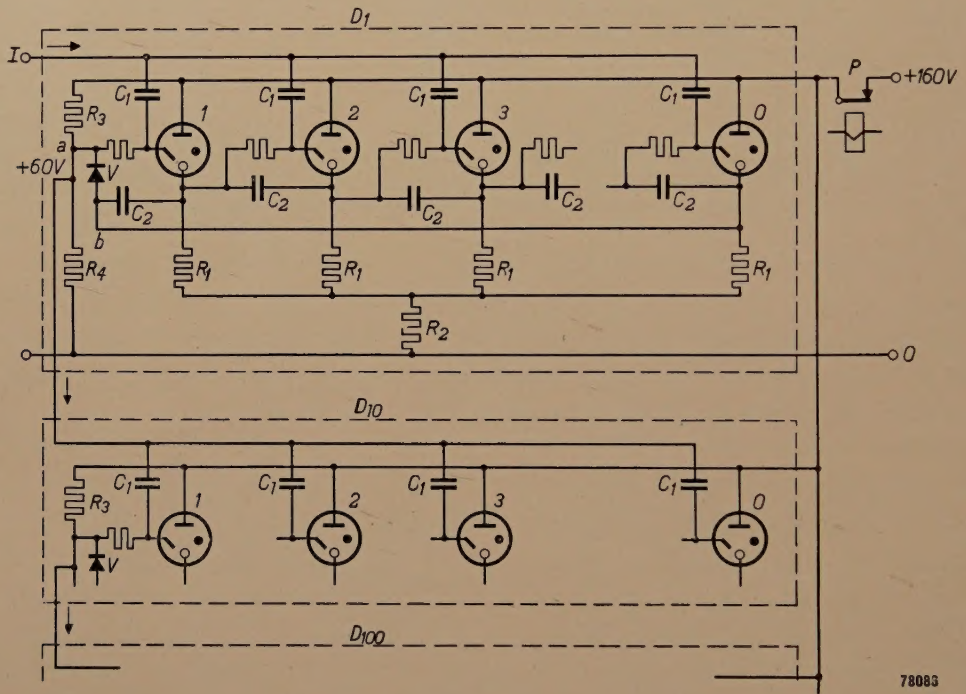

Fig. 9. Decade-counter employing cold-cathode tubes. D_1 units decade, D_{10} tens decade, D_{100} hundreds decade, each containing 10 tubes Z 500 T (*1*, *2* ... *0*). *I* input terminal. C_1 input capacitors. R_1 cathode resistors. R_2 common cathode resistor. C_2 quenching capacitors. R_3-R_4 voltage divider, from which the +60 V trigger electrode bias of the first tube is derived. *V* rectifier element through which the tubes of the next decade are ignited. *P* re-set contact, which is opened momentarily after counting, to extinguish all tubes.

A description of a special decade counting tube (type E1T) and the counting circuit designed for it, was published recently in this Review[4]). It may be of interest to draw a brief comparison between this tube and the tube Z 500 T.

Some characteristic advantages of the E1T are:

1) The maximum counting speed is far greater.
2) The tube E1T in itself constitutes a decade, so that one tube E1T (together with an auxiliary valve E 90 CC) takes the place of 10 tubes Z 500 T.

As regards item 1), the counting circuit of the E1T is capable of counting speeds of at least 30,000 pulses per second; far greater speeds can be attained with special circuit adjustments to suit individual tubes, and with the aid of certain auxiliary tubes. For the gas-discharge tube, the counting speed is, in principle, limited, firstly by a delay depending on the number of electrons (mainly photo-electrons) fortuitously present in the tube just before ignition, and furthermore by the period required for building up the starting discharge and the main discharge, and finally by the de-ionization (quenching) time. The maximum counting rate lies somewhere between 1500 and 2500 pulses per second (which is considerably more than is required for telephony purposes).

On the other hand, the cold cathode tube Z 500 T shows the following advantages:

1) no filament current is required;
2) the "gross" life is longer;
3) less heat is generated;
4) the supply voltage is lower (160 V compared to 300 V);
5) a counting circuit with tubes Z 500 T not only gives a visual indication of the counted number, but also gives an indication in terms of voltages: the anode or cathode potential of ignited tubes is different from those of non-ignited tubes; these marking voltages (see below) can be used, for example, for the ignition of other tubes.

The above considerations show that the existence of both types of tubes is justified.

To reset the circuit after a count, the tubes can be extinguished by a short interruption of the supply voltage, for example, by a relay-contact (*P*, fig. 9).

Register circuit

With certain automatic telephone systems, the numbers dialled by a subscriber are temporarily recorded by means of switches or relays in "registers"; after the whole number has been dialled, the registers determine the positions to be taken up by the selectors in order to establish the connection with the called subscriber. All the electro-mechanical devices usually employed for this purpose can be replaced by cold-cathode tube circuits. One decade of the counting circuit described above then serves for both counting and marking. The group of registers comprises a number of decade registers, one for each digit in the telephone number. The counting-and-marking circuit counts the number of pulses generated each time a digit is dialled, marks the corresponding tube of the relevant register, so that this tube is also ignited, and then returns to its initial position in order to count the pulses of the next digit. This counting-and-marking circuit will from now on be referred to, for short, as a "counter".

Consider the example of a telephone system with three-digit numbers. A subscriber wishes to be connected to number 382. The number 3 is first dialled. The returning dial produces three pulses, so that tube *3* of the counter will be left ignited. This causes tube *3* of register *I* to ignite, whereupon tube *3* of the counter extinguishes. (The manner of doing this will be described later.) The subscriber now dials 8: tube *8* of the counter ignites, tube *8* of register *II* ignites, and tube *8* of the counter is extinguished. A similar procedure takes place with the third digit. As a result, the selected number is recorded by the burning of tube *3* in register *I*, tube *8* in register *II* and tube *2* in register *III*.

All this can be effected by the circuit represented in *fig. 10* (for simplicity, only two registers are shown; more registers, however, can simply be added to this diagram). The counter (*C*) is similar to the decade circuit shown in fig. 9, with the exception that there is now no connection between tube *0* and tube *1*, since the counter is not required to count more than 10 pulses. If three pulses are applied to the counter, then, as described in the previous section, tube *1* is ignited by the first pulse, tube *2* by the second pulse (whereupon tube *1* extinguishes) and tube *3* by the third pulse (whereupon tube *2* extinguishes); the ignition of a tube means that its cathode reaches a potential of approx. 100 V, the marking voltage. The cathode of each counter tube is connected to the trigger electrode of the corresponding tube in register *I*, so steps must be taken to ensure that while the prolonged burning of tube *3* (in this example) causes registration in *I*, the transient burning of the counter tubes *1* and *2* are *not* recorded in register *I*. The distinction between these burning periods is made with the aid of the time-delay networks R_5-C_3. The effective delay is greater than the interval between two consecutive pulses, so that the trigger electrodes of the register tubes *1* and *2* cannot attain the ignition voltage (65-78 V); the trigger electrode of tube *3*, on the other hand, has ample time in which to do so.

The counter must now be returned to its initial state in order to be ready to deal with the next number dialled, i.e. the counter tube *3*, which is still burning, has to be extinguished. This is done by the action of an auxiliary tube (*E*). When a tube of register *I* is ignited, a current passes through resistor R_7, which raises the potential of point *p* from 0 to 50 V. This voltage surge passes through the capacitor C_5 and ignites the tube *E*, the trigger electrode of which already had a 60 V bias, derived from a voltage divider R_8-R_9. Incorporated in the cathode circuit of tube *E* is a resonant circuit (L_0-C_4, with a resistor in parallel to C_4). On ignition of tube *E*, the condenser C_4 is charged through L_0. The voltage across C_4 is applied through a coupling capacitor (C_7) to a tapping on the resistor R_2; this voltage increases sufficiently to extinguish the burning counter tube. Tube *E* itself is extinguished when the voltage across it drops below the sustaining voltage. This happens because the inductance L_0 prolongs the flow of the condenser charging current after the voltage across the tube has dropped to its sustaining voltage. The net result is thus that the first digit, 3, is recorded in register *I* (i.e. tube *3* in register *I* is burning), while the counter and the auxiliary tube *E* have returned to their initial condition.

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[4]) A. J. W. M. van Overbeek, J. L. H. Jonker and K. Rodenhuis, A decade counter tube for high counting rates, Philips tech. Rev. 14, 313-326, 1953 (No. 11).

The subsequent digit has to be recorded in register *II*. This is effected in the following manner. The burning tube of register *I* produces a 50 V voltage drop across resistor R_7, and this is used to render register *II* sensitive and register *I* insensitive to whatever marking voltage occurs in the counter during the dialling of the second digit. In fig. 10 it is seen that the trigger electrodes of register *II* are connected to the tappings *q* of the voltage dividers R_{10}-R_{11}, the lower part of which (R_{11}) are varistors. These voltage dividers have been so proportioned that, at a marking voltage of 100 V, point *q* assumes a potential of 60 V or 90 V, according to whether the potential of the point *p* is 0 (initial state) or 50 V (already registering) respectively.

Now consider again the counting of the pulses

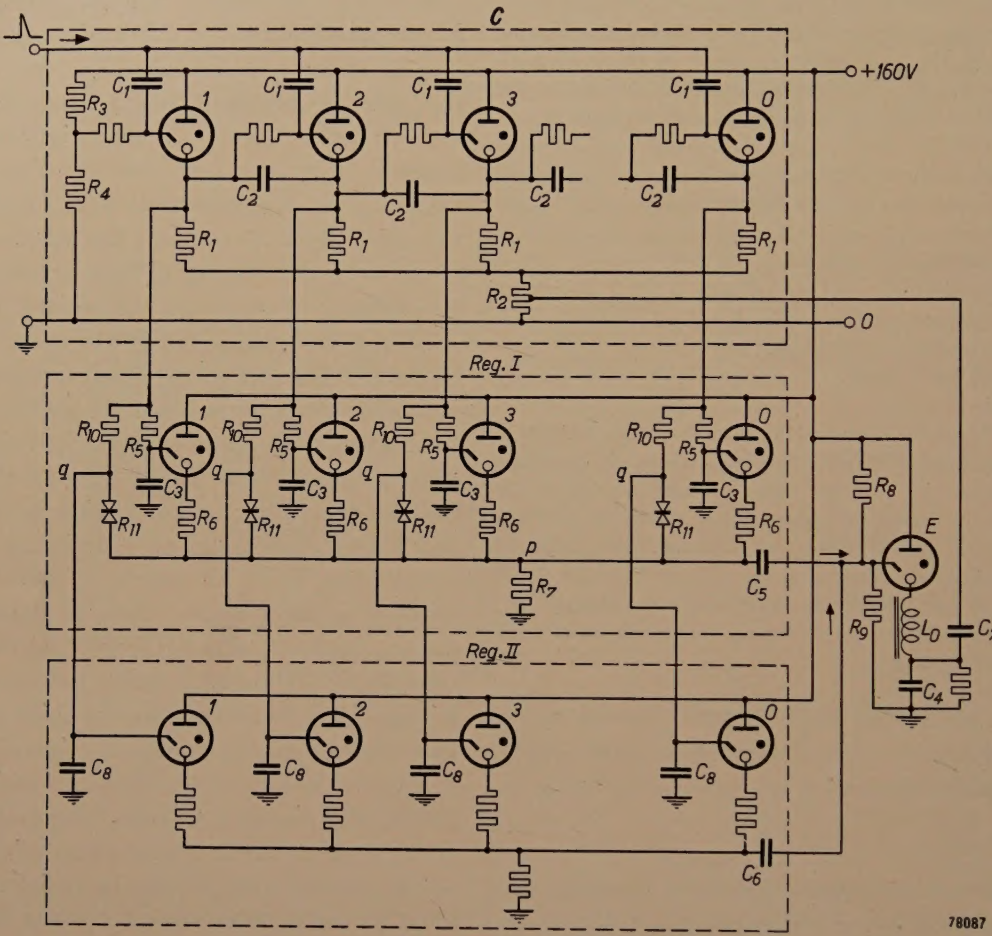

Fig. 10. Counting and marking circuit (*C*) with two registers (*Reg. I* and *Reg. II*). The circuit of *C* is almost the same as that of decade D_1 in fig. 9. *E* quencher tube, which, after a digit has been recorded in a register, extinguishes the tube burning in *C*. R_5-C_3 delay networks, preventing the transient burning of the tube in *C* influencing *Reg. I*. R_{10}, R_{11} and C_8 constitute similar delay networks for *Reg. II*.

of the first digit by C (fig. 10). The potential of point p is then still zero, and the potential of 60 V assumed by the marked point q is not sufficient to ignite the corresponding tube of register *II*, but the full marking voltage is available to ignite the corresponding tube of register *I*. The first digit is thus recorded in register *I*, but not in register *II*.

When the second digit is being dialled, the point p, and therefore also the cathode of the non-burning tubes of register *I*, are already at a voltage of 50 V. The result of this is that this register is blocked for the second digit. The voltage at the marked point q is now not 60 V, but 90 V, so that the second digit will be recorded in the second register. The auxiliary tube E is then again fired by a pulse (via C_6), and operates as before to return the counter to its initial condition.

The capacitors (C_8) between the trigger electrodes and earth ensure that the transient burning of the counter tubes cannot influence the register.

The cold-cathode tube in speech-current circuits

A speech current may be superimposed on the direct current of a few milliamps flowing through the cold cathode tubes. The gas discharge constitutes a certain impedance to this alternating current. This impedance, by analogy with the contact resistance of a relay contact, should be kept as low as possible. The impedance depends on the frequency, and on the intensity of the direct current and, with regard to the tube, on the gas filling, the geometry of the electrodes and the work function of the cathode material [5]). The oxide cathode results in a low value of the work function, which gives a low impedance. At a current of 6 mA and frequencies between 300 and 3000 c/s, the tubes have an impedance of approximately 500 Ω. Such a value may be considered low for a gas discharge, but is still fairly high when compared with the contact resistance of a relay contact. In order to keep the attenuation caused by the discharge impedance as low as possible, it is necessary that the impedance of the circuit in which the tube functions, is increased as much as possible without giving rise to "crosstalk". If the impedance of the circuit can be stepped up in this way to say, 2400 Ω, the attenuation caused by the tube will only be 1 dB.

Engaged-test and blocking

In automatic telephony it is a common occurrence that a free line has to be selected from a bundle of lines. Two conditions as regards "blocking" then have to be satisfied:

1) Once a free line has been found, no subsequent connection with a second free line must be made.
2) Only one connection must be possible with the free line found.

Using electro-mechanical devices, this selection generally proceeds by a switch scanning the lines one at a time, and stopping upon finding the first free line. Electronic devices, on the other hand, are capable of a *simultaneous* examination of all lines, whilst at the same time meeting the blocking conditions. The time saved by this simultaneous examination may result in a saving in equipment.

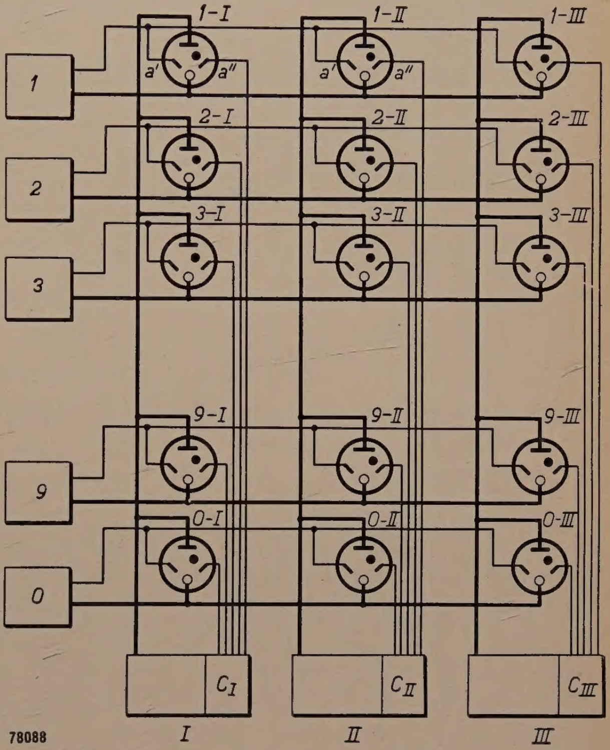

Fig. 11. Block diagram of an electronic telephone exchange for 10 lines. *I*, *II*, *III* connecting-circuits, each with a counting and marking circuit C_I, C_{II}, C_{III} (like C in fig. 10). *1-I*, *1-II*, ... *0-III* are 30 cold-cathode tubes Z 501 T.

Fig. 11 shows the principle of an electronic circuit having the above-mentioned properties, for a small, ten-line exchange. To the left are the subscribers' sets, numbered *1*, *2*, ... *0*. Within the exchange, the connections between the subscribers can be established via connecting-circuits — in this case there are three (*I*, *II*. and *III*) — by means of 3 × 10 = 30 cold-cathode tubes, placed at the junctions of the subscribers' lines and the connecting-circuits. Here the tubes with two trigger electrodes (type Z 501 T) can be used with advantage.

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[5]) See C. van Geel, Untersuchungen von Gasentladungen mit Rücksicht auf ihre dynamischen Eigenschaften und ihre Stabilität, Physica **6**, 806-816, 1939.

As an example, suppose subscriber *2* wishes to telephone subscriber *9*. When the receiver is lifted from its cradle, one of the speech current tubes *2-1*, *2-II* or *2-III* is ignited, and the subscriber *2* becomes connected to one (and only one) of the connecting circuits. Once this connection has been established, this connecting circuit must be blocked for other calls. Should all the connecting circuits be in use at the moment the receiver was lifted off the cradle, then the subscriber should hear the busy-signal.

After the connection to one of the connecting circuits, e.g. to circuit *II*, has been established, subscriber *2* dials number 9. The pulses thus produced are counted by counter C_{II} of connecting circuit *II*, so that tube *9* in this counter ignites. This causes tube *9-II* to be ignited, which serves as a selector contact and establishes the connection between subscriber *2* and subscriber *9*. If subscriber *9* should be engaged, then subscriber *2* must hear the busy-signal; otherwise the bell of set *9* must ring. The production and circuiting of the busy-signal and the ringing current will be dealt with later on in this article.

From the above description it will be clear that first a horizontal row of tubes (row *2*) has served as a pre-selector and then a vertical column (column *II*) as a final selector. Any of the thirty tubes must therefore be suitable for both functions. In order that the tubes may play both roles, tubes with two trigger electrodes have been employed; the trigger electrodes *a'* function if the tube is used as a pre-selector, and the trigger electrodes *a''* function if the tube is used as a final selector. (This is not absolutely necessary; tubes having one trigger electrode can also be used, but in that case each tube requires, among other things, a rectifier element whose resistance in both conduction directions has to be accurate within fairly narrow limits. Consequently, tubes having two trigger electrodes are preferred here.)

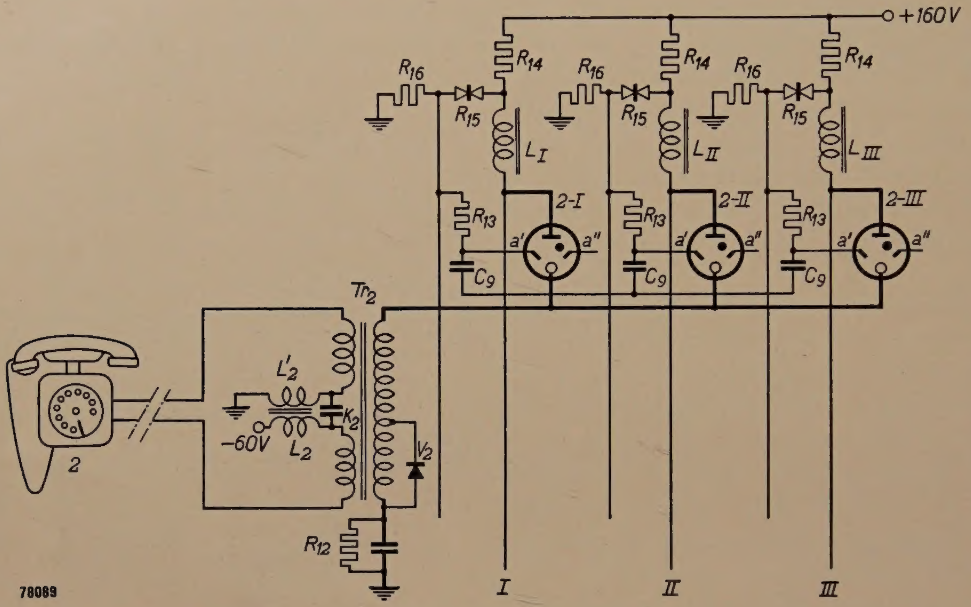

Fig. 12. Part of the circuit of fig. 11, further developed and slightly modified. Tr_2 transformer coupling the (symmetrical) line of subscriber *2* to the (asymmetrical) connecting circuits *I*, *II* and *III*. The choke coils L_I, L_{II} and L_{III} prevent the 160 V battery presenting a short-circuit to the speech current. The voltage dividers R_{15} (varistor)-R_{16} apply a +60 V bias to the trigger electrodes *a'*. If the subscriber is connected up to one of the free connecting-circuits, a voltage drop occurs in the resistor R_{14} of the active circuit and in the common resistor R_{12}. This voltage drop is such that the remaining circuits are blocked to him, and also the active connecting-circuit becomes inaccessible to the other subscribers, whilst his own line is marked as being engaged. The capacitors C_9 ensure that the ignition of the auxiliary discharge via *a'* is sufficient for temporarily preventing more than one tube igniting at the same time. The coils L_2-L_2' keep the speech current out of the 60 V battery and constitute a step-up autotransformer of ratio 1 : 2 for the ringing voltage (see under *Ringing current*). The capacitor K_2 and the one in parallel with R_{12} provide paths for the speech current. The rectifier element V_2 limits the negative voltage pulse which occurs when the subscriber lifts the receiver.

Fig. 12 demonstrates in greater detail the procedure of selecting a free connecting circuit. All 30 tubes — only three are shown — are supplied with a direct voltage of 160 V, and the trigger electrodes a' are given a bias of 60 V by the voltage dividers R_{15}-R_{16}. The coupling between the connecting circuits, which are asymmetrical with respect to earth, and the symmetrical subscribers' lines, is effected by means of transformers, such as Tr_2, which also step up the voltage so as to minimize the attenuation caused by the cold-cathode tubes. The microphone current is supplied by a 60 V battery, via the transformer L_2-L_2'. The speech current passes through the capacitor K_2 and is kept out of the battery. The circuit of the microphone is closed only when the calling subscriber lifts the receiver from the cradle. The closing of this circuit causes a voltage pulse in the secondary coil of the transformer. At the cathode side of the tubes of row *2* this pulse has a negative polarity. A rectifier element (V_2), which bridges part of the secondary of Tr_2, limits the amplitude of the pulse to approximately 25 V, which makes the cathodes sufficiently negative with respect to the trigger electrodes a' to permit ignition.

Now assume that all connecting-circuits are free. One of the tubes of row *2*, e.g. tube *2-II*, is thus ignited, so that subscriber *2* is connected up with a connecting-circuit. The current then flowing through the tube causes a voltage drop of 60 V across resistor R_{12}, which raises the cathode potential of the remaining tubes of row *2* to such a value that these tubes can no longer be ignited.

There could, however, still be a remote chance that the pulse will ignite more than one tube. During the short interval of 10^{-4}-10^{-5} sec, in which the auxiliary discharge is established but the main discharge has not yet started, the voltage produced across R_{12} is not yet high enough to block the other two tubes. In order to prevent another tube igniting within the above interval, the three trigger electrodes a' are coupled to each other by capacitors (C_9). If now an auxiliary discharge is initiated in one of the three tubes, then the potential of the relevant trigger electrode will drop, due to the voltage drop across resistor R_{13}, and the capacitors will temporarily transfer this drop to the trigger electrodes of the other two tubes. The latter two are thus blocked — even though the *main* discharge in the first tube has not yet been initiated — thus precluding the possibility that a subscriber would be simultaneously connected with more than one connecting-circuit.

The second condition for blocking, viz. that an engaged connecting-circuit cannot possibly be reached by the other subscribers, is satisfied in the following manner: If, as in our example, subscriber *2* is connected, via tube *2-II*, to connecting-circuit *II*, then a voltage drop of 40 V will occur across resistor R_{14} of this circuit, so that the voltage across $R_{15}+R_{16}$ is also reduced by this amount. This causes the voltage at the tapping on R_{15}-R_{16} to be reduced by nearly the same amount (30 V), owing to the fact that R_{15} is a varistor. The potential at the trigger electrodes a' of the other tubes which might give access to connecting-circuit *II*, is thereby lowered so far that the engaged connecting-circuit can no longer be reached. If, at the moment that subscriber *2* lifted his receiver, one or two connecting-circuits were already engaged, then the relevant tubes, due to insufficient bias of their trigger electrodes a', could not ignite. It is clear that with this electronic circuit, the test for a free connecting-circuit, in fact takes place simultaneously.

We have seen how the subscriber, by lifting his receiver, has been connected to a free connecting-circuit. It now remains to consider how dialling establishes a connection with the called subscriber, how the latter is given ringing current, or how the former receives the busy-signal, and finally how, on replacing the receiver on the cradle, the connection is broken.

Final selector

As we have assumed, tube *2-II* has been ignited by the raising of the receiver *2*. When now a number is dialled, the return of the dial produces square current pulses (*fig. 13a*). This induces in the coils of transformer Tr_2 a voltage proportional to the derivative of the current, i.e. consisting of positive and negative pulses (fig. 13*b*). These pulses are also present across the choke coil L_{II} (*fig. 14*, which shows only the calling set *2* and the called set *9*, and only circuit *II* of the connecting-circuits), which prevents the 160 V battery from constituting a short-circuit for the speech currents. The ampli-

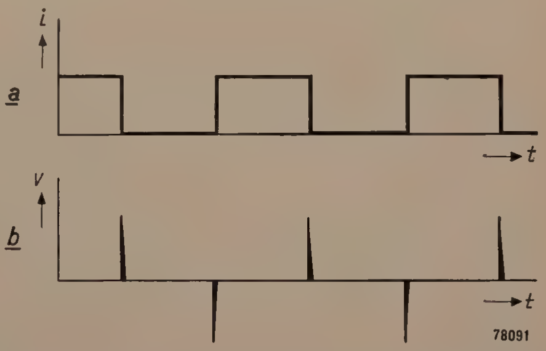

Fig. 13. After dialling a digit, the returning dial periodically breaks and closes a contact in the microphone-current circuit. The square pulses so generated (a) induce positive and negative voltage pulses (b) in the secondary winding of transformer Tr_2 (fig. 12).

tude of the pulses applied to L_{II} depends on the length of the subscribers' line, but counter C_{I}, which has to count the negative dialling pulses, requires positive pulses with an amplitude of approximately 30 V (as explained under *Counting circuit*). For this reason, an amplifier and a pulse-shaping circuit have been incorporated between the choke coil L_{II} and the input of counter C_{II} (fig. 14). The amplifier (A_1) consists of one half of a double-triode ECC 81, which is so biassed that only negative pulses are amplified (*fig. 15*); the amplifier output thus consists of positive pulses only. The pulse-shaping circuit (*PS*) contains a cold-cathode tube Z 500 T (*fig. 16*), which, owing to a trigger electrode bias of +60 V, reacts to the positive pulses from A_1, and supplies positive pulses of constant amplitude to the counter.

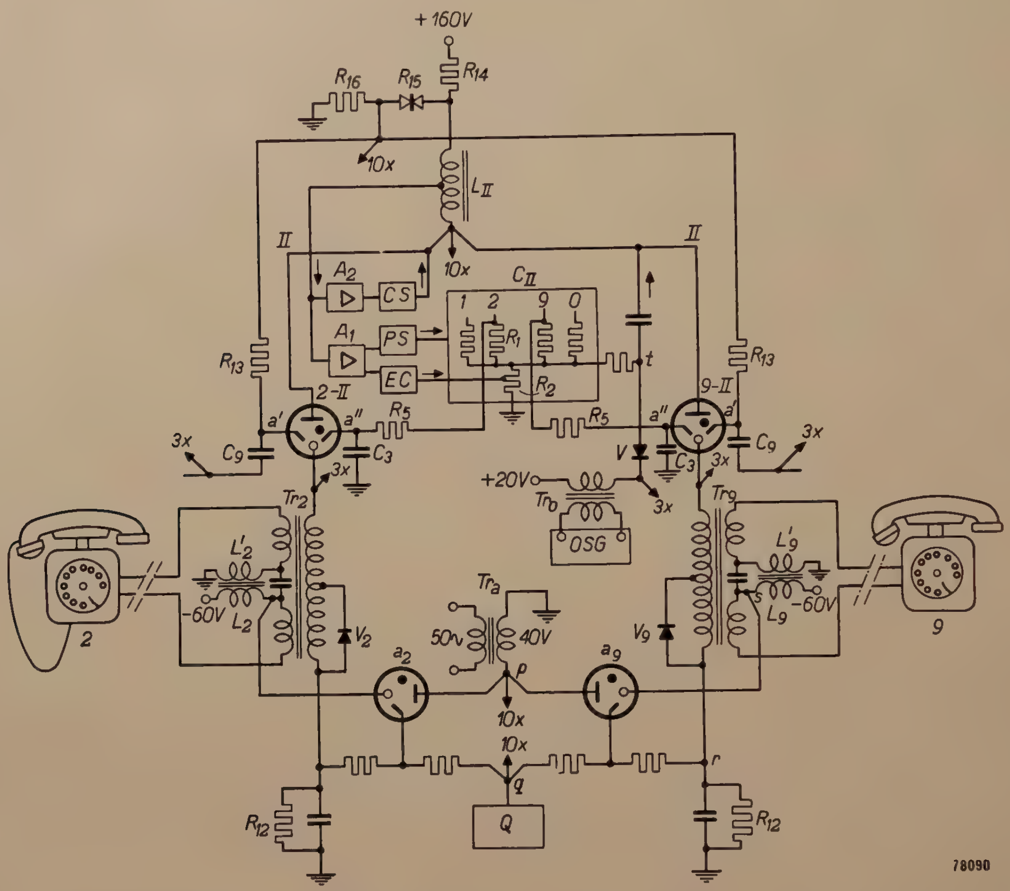

Fig. 14. Diagram showing the signalling and the speech connections between two subscribers (*2* and *9*), in an electronic telephone exchange. Of the three connecting-circuits and the 30 speech current tubes (cf. fig. 11) only the connecting-circuit *II* and the tubes *2-II* and *9-II* are shown (the arrows marked 3× and 10× indicate that in the actual exchange a threefold or tenfold connection is present).

A_1, A_2 amplifiers. *PS* pulse-shaping circuit. C_{II} counting and marking circuit (*C*, fig. 10) of the connecting-circuit *II*. *EC* quenching device of C_{II}. *CS* quenching device for the speech current tubes. Tr_a ringing-current transformer (50 c/s). a_2, a_9 tubes transmitting the ringing current to subscribers *2* and *9* respectively. *Q*= multivibrator determining the ringing "pattern" (1 sec on, 5 sec off). *OSG* busy-signal generator, with output transformer Tr_o. *V* rectifier element normally blocked, which becomes conducting, however, if an engaged subscriber is called, and passes the busy-signal. R_5-C_3 delay networks as in fig. 10. The remaining letters and symbols have the same meanings as in fig. 12.

After 9 has been dialled, tube *9* of the counter ignites and, as explained in the description of the register circuit, tube *9-II* is thus ignited (by the trigger electrode *a''*), provided, at least, that line *9* is not engaged at that moment.

The burning counter tube has subsequently to be extinguished. This is done by using the sudden and substantial voltage drop occurring at the anode of tube *9-II* during ignition of the latter (voltage drop across R_{14}). A_1 converts this pulse into an amplified pulse of opposite polarity, which, with the aid of a quenching device (*EC*, fig. 14), extinguishes the burning counter tube. The latter process occurs exactly analogously to that in the register circuit (tube *E* in fig. 10). (The cold-cathode tube in *EC* has a trigger electrode bias of only +35 V and is thus less easily triggered than the tube of the pulse-shaping circuit *PS*: consequently it reacts to the ignition of tube *9-II*, but not to the dialling pulses.)

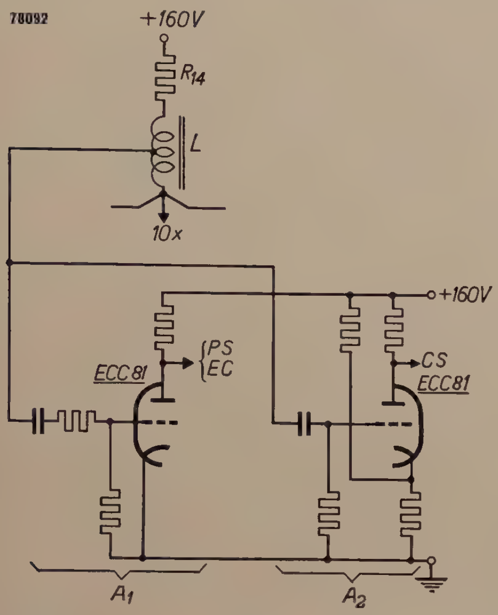

Fig. 15. Diagram of the amplifiers A_1 and A_2 (fig. 14), each using half of a double-triode ECC 81. A_1 is given no grid-bias and consequently reacts to negative pulses only, and only positive pulses occur at the anode, which are applied to the pulse-shaping circuit *PS* and to the quenching device *EC*. A_2 is cut-off by a bias of —8 V, which renders all negative and also small (unwanted) positive pulses ineffective, whereas large positive pulses are amplified into negative pulses at the anode, which are applied to *CS*.

Ringing current

After the tubes *2-II* and *9-II* have been ignited, the ringing current has to be circuited to the called subscriber *9*. The signal generally used for ringing is an alternating voltage with a frequency of 17-25 c/s, generated by an alternator which is often driven independently of the mains. In our experimental exchange, however, for reasons of convenience, a mains transformer (Tr_a, fig. 14) has been employed giving an output of 40 V, 50 c/s. Point *p* of the secondary winding is connected to the anodes of 10 more cold-cathode tubes (one for each subscriber's line), of which only tubes a_2 and a_9 are shown in fig. 14. In order to ring subscriber *9*, tube a_9 has to be ignited.

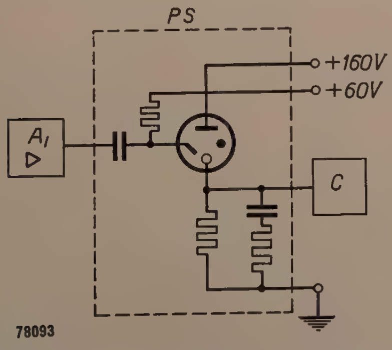

Fig. 16. Diagram of the pulse-shaping circuit (*PS*, fig. 14). A negative pulse of variable amplitude at the input of the amplifier A_1 (fig. 15) creates a positive pulse at the input of *PS*, which ignites the cold-cathode tube. The capacitor in parallel with the cathode resistor (in series with a low-value resistor for limiting the charging current) is charged and thus causes the tube to extinguish. A voltage pulse of constant amplitude is produced at the cathode, which is applied to the counting and marking circuit *C*.

The trigger electrode of this tube is connected to a tapping on a voltage divider connected between points *q* and *r*. For the time being, we shall assume the potential of *q* to be zero, and as long as tube *9-II* is non-conducting, the potential of point *r* and that of the trigger electrode of a_9 are also zero. Since the cathode of tube a_9, connected to point *s*, has the potential —60 V, the tube cannot be ignited in this condition.

Once tube *9-II* is ignited, the potential of point *r* rises from 0 to 45 V owing to the voltage drop across resistor R_{12} between *r* and earth, and the trigger electrode of a_9 is given a voltage sufficiently high for ignition to take place. This tube then transmits the 50 c/s ringing pulses: across the anode circuit is a direct voltage of 60 V, and an alternating voltage of 40 V (r.m.s.), 50 c/s, so that the voltage across the tube fluctuates between approx. 4 and 116 V. Hence the tube is extinguished each cycle. The telephone set *9* now rings (the coils L_9-L_9' functioning as an autotransformer, stepping the voltage up in the ratio 1 : 2), until the receiver is lifted from the cradle. At that moment microphone current commences to flow through coil L_9; owing to the resulting voltage drop, the potential of point *s* (and hence of the cathode of a_9) will be raised from — 60 V to — 30 V, so that a_9 cannot re-ignite. For the same reason subscriber *9* cannot receive a ringing current while being engaged in a call with another subscriber.

This likewise explains why tube a_2 was not ignited the moment subscriber *2* lifted his receiver, which, of course, results in a current through tube *2-II* and its associated resistor R_{12}. Although this current causes the trigger electrode potential of tube a_2 to rise, the microphone current simultaneously increases the cathode potential from —60 V to —30 V.

Fig. 17 shows one of the sliding panels of the experimental electronic exchange, containing the components particular to two subscribers, e.g., two subscriber's line transformers, 2 × 3 speech-current tubes and two ringing-current tubes.

The ringing current commonly used is not a continuous, but a periodically interrupted current, This has been obtained here by making the potential of point q alternately zero and —45 V, viz. zero for one second and —45 V for five seconds.

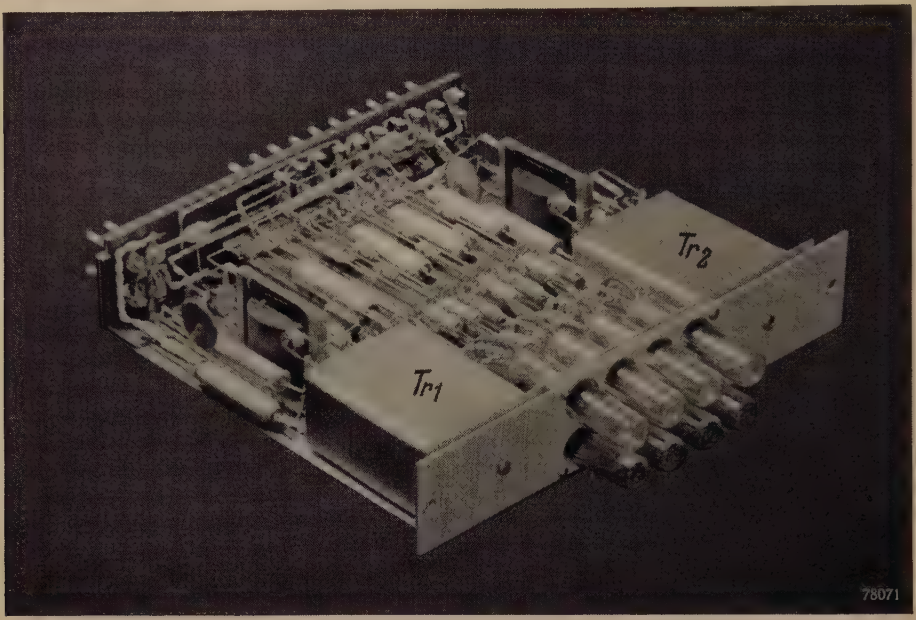

Fig. 17. One of the upper five sliding panels of the exchange in fig. 5. Tr_1 and Tr_2 are two subscriber's line transformers. In between them there are two ringing-current tubes and 2 × 3 speech current tubes.

While a potential of —45 V prevails at the point q, tube a_9 cannot ignite, even if point r has a potential of +45 V. The potential variation of point q is effected by a multivibrator Q. *Fig. 18* shows a multi-vibrator circuit with cold-cathode tubes, an explanation of which is given in the caption.

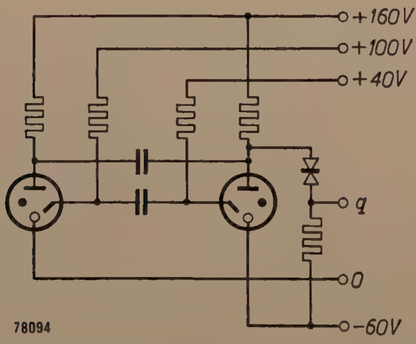

Fig. 18. Diagram of a multivibrator employing cold-cathode tubes (Q in fig. 14). The tubes are alternately conducting; owing to the different resistances in the trigger electrode circuits, the right-hand tube burns for 5 sec and the left-hand tube for 1 sec. The potential of point q (fig. 13) is therefore alternately —45 V for 5 sec, and zero for 1 sec, which determines the ringing "pattern".

Busy signal

In two cases the calling subscriber will hear the busy signal: 1) if the called subscriber's line is engaged, and 2) if all connecting-circuits are engaged the moment the calling subscriber lifts his receiver off the cradle.

Case 1 : Called subscriber's line engaged. The equipment required in this event is illustrated in fig. 14. *OSG* is the busy signal generator, supplying a periodically interrupted voltage of e.g. 800 c/s. This signal is fed through a transformer Tr_0. Normally, however, the passage of this signal is blocked by a rectifier element (V), the cathode of which, apart from a small alternating voltage, has a permanent potential of +20 V, whereas its anode (point t) is normally at zero potential.

If subscriber *2* dials *9*, then tube *9* will ignite in counter C_{II}. When subscriber *9* is engaged, however, via connecting-circuit *I* or *III*, tube *9-II* does not ignite, since the current flowing through the resistor R_{12} of set *9* gives the cathode of tube *9-II* a potential of +45 V, which prevents ignition. As tube *9-II* does not ignite, the quenching device (via A_1-*EC*, see above) for tube *9* of C_{II} does not come into action. Counter tube *9* thus remains burning (and is not extinguished until subscriber *2* replaces his receiver on the cradle), the voltage at point t increases and rectifier element V conducts, so that the busy signal now passes to the connecting-circuit *II* and is heard in the receiver of subscriber *2*.

Case 2 : All connecting-circuits engaged. For this case we refer to *fig. 19*, which shows again the busy-signal generator *OSG* and the transformer Tr_0. The latter has a third winding connected to the anode side (g) of a rectifier element V'. If the direction of the steady potential across the element is such that it is conducting, then the third winding supplies an alternating current, via a capacitor C_0, to the secondary of transformer Tr_2, and the subscriber hears the busy-signal. This steady potential is present across the rectifier element only when the subscriber has lifted his receiver from the cradle whilst all connecting circuits are engaged.

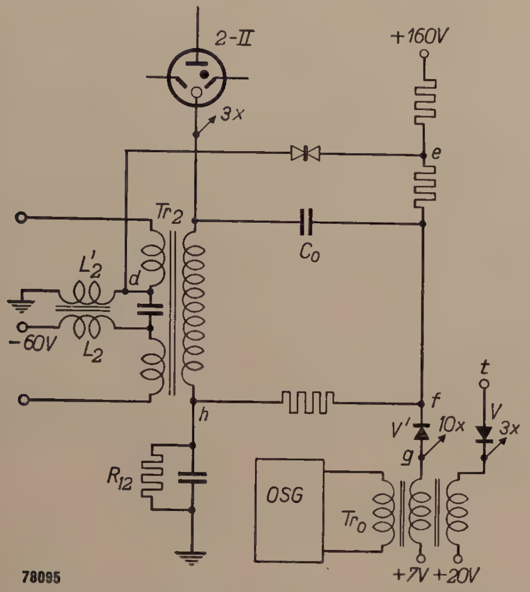

Fig. 19. If all connecting-circuits are engaged, the subscriber, on lifting his receiver, must hear the busy-signal. In that case the rectifier element V', which is normally blocked, becomes conducting, and the busy-signal from generator *OSG* passes through the transformer Tr_0, the rectifier V' and the capacitor C_0, to the transformer Tr_2 and thence to the subscriber's line.

This is seen as follows. The anode side of the rectifier element, point g, has (apart from a small alternating voltage) a permanent potential of +7 V. The element is therefore not conducting if the potential V_f of the cathode side f is in excess of 7 V, but it does conduct if $V_f \leq 7$ V. The potential V_f is in fact the mean value between the potentials V_e of point e and V_h of point h. V_e depends on potential V_d of point d, which in turn depends on whether the receiver is on its cradle or not:

receiver on cradle . . . . $V_d = 0$, $V_e = 25$ V;
receiver lifted . . . . . . $V_d = -30$ V, $V_e = 0$.

V_h depends on the current through resistor R_{12}. If all connecting circuits are engaged, then tubes *2-I*, *2-II* and *2-III* cannot ignite, hence $V_h = 0$; if, on the other hand, the subscriber does become connected to a connecting-circuit, then V_h will assume the value of +60 V if one tube is burning (e.g. *2-II*), and of +45 V if two tubes are burning (e.g. *2-II* and *9-II*).

There are thus 2 × 3 possible combinations, but in only one of these — the case where the receiver is lifted and all connecting circuits are engaged — can V_f become sufficiently low for the rectifier V' to conduct and thus pass the busy-signal. In all other cases, V_f remains above 7 V.

Fig. 20 shows the circuit of a busy-signal generator incorporating two cold-cathode tubes. The left-hand tube generates a non-sinusoidal voltage at a fundamental frequency of 800 c/s. This oscillation is interrupted for a short moment by the right-hand tube at intervals of 1 sec.

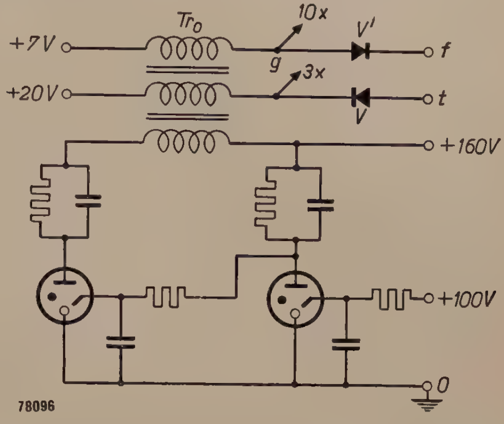

Fig. 20. Diagram of a busy-signal generator with cold-cathode tubes. The left-hand tube operates as a relaxation oscillator with a fundamental frequency of 800 c/s, but is interrupted for a fraction of each second by the right-hand tube which operates similarly at a fundamental frequency of 1 c/s. Tr_0 is the output transformer (see figs 14 and 19).

Terminating the call

After completion of the call, the tubes *2-II* and *9-II* have to be extinguished. This is effected by either of the subscribers replacing his receiver on the cradle. By doing this he breaks his microphone current; this results in a positive pulse being applied to the occupied connecting-circuit. This pulse is amplified by an amplifier (A_2 in fig. 14) and its polarity is reversed (A_2 is the other half of the tube ECC 81 of A_1, and is so biassed that only positive pulses are amplified, see fig. 15). The negative pulse at the output of A_2 activates a quenching device (*CS*), which extinguishes tubes *2-II* and *9-II*.

In the event of subscriber *9* having been engaged, the counter tube *9* is, furthermore, extinguished.

Larger electronic telephone exchanges

The electronic exchange (fig. 5) dealt with in this article has been intended for purposes of demonstration and testing in practice. For as many functions as possible, cold-cathode tubes have been employed. Meanwhile, designs have been made for installations on a larger scale, such as exchanges for 1000 and 10 000 subscribers. Only then can the saving in material which is potentially possible by the application of inertia-free controlling devices, be shown to full advantage. Electronic registers and selectors require fewer controlling devices than slower-acting equipment.

It would be pedantic, however, to insist that all or nearly all tubes for these designs should necessarily be of the cold-cathode type. On the contrary, all possibilities should be carefully considered and compared on their merits. This exhaustive task is still proceeding. It is certain, however, that in automatic telephony and allied fields, these new tubes are destined for a wide range of applications.

Summary. This article deals with the application of oxide-coated cold-cathode gas-discharge tubes, fitted with one or two trigger electrodes (types Z 500 T and Z 501 T, respectively), for switching operations in automatic telephone exchanges and related fields. The tube is argon-filled and operates by means of a glow-discharge. With the trigger electrode(s) unbiassed, the breakdown voltage of the tube is higher than 175 V between anode and cathode; when a discharge between cathode and trigger electrode exists, the breakdown voltage lies between 175 V and approx. 70 V (depending on the trigger electrode current). The ignition voltage of the trigger electrode is between 65 and 78 V. At an anode current of 6 mA, the tube presents an impedance of approx. 500 Ω to speech currents. The life expectancy of this type of tube is over 6000 hours (actual burning time) and may be considerably in excess of this. Numerous circuits for this type of tube are reviewed, demonstrating that it can serve as a relay (with all kinds of contact combinations), in counters, marking circuits, registers, pre-selectors, final selectors, signalling circuits, multivibrators, etc. Most of the circuits described are part of an experimental, fully-electronic telephone exchange, which has already been functioning for some years in the Philips Research Laboratory in Eindhoven.

RADIO-CONTROLLED MODELS

by A. H. BRUINSMA.

621.398

It is perhaps a deplorable fact, that toys often take the form of models of military weapons and machines. In the war of 1940-1945 the position was reversed: a "toy", viz. remote control of models by radio, was developed for the remote control of weapons. Since the war the development of the technique of radio control has led to still more advanced models, both for toys and for serious scientific investigations.

The idea of controlling equipment from a distance by means of electromagnetic waves is roughly as old as radio broadcasting itself. Wireless-controlled boats were made some 25 years ago, but development proceeded slowly for various reasons; one of the greatest problems was that of the necessary supply voltages for the uneconomical valves then available. It was therefore usual to employ super-regenerative receivers which required only a small number of valves. The various "instructions" were transmitted by means of a rotary "escapement" switch, which meant that the instructions could be executed only one at a time, resulting in a certain lack of flexibility in control. The technique did not emerge from the amateur stage until its war-time possibilities were exploited during and after the second world war. These advances owed much to the development of high frequency techniques which greatly simplified the problem of the aerial. Radio-controlled aircraft, projectiles, tanks and boats were made, in which this method of control reached new levels of refinement and reliability.

For peace time purposes, too, radio-control is becoming more and more important. Aircraft designers, for example, can study radio-controlled prototype models, which permit enormous economies in the early stages of new designs. Human life, time and money can be saved in the early training of pilots by first giving them practice with radio-controlled pilotless aircraft. Scientific research in the ionosphere by means of controlled rockets is yet another instance. Radio control of toy models — the oldest member of the family — is now also a growing field of application. The possibilities, particularly in the last-mentioned field, are now considerably widened as a result of the introduction of miniature battery valves of low current consumption. In order to investigate the possibilities, two circuits have been designed for radio-controlled models which, for practical reasons, are in the form of model boats.

Design of the models

Where precise manoeuvrability of a model is of importance, one of the first requirements is the execution of the control orders with the minimum delay, or even simultaneously. This, of course, is not possible when an escapement switch is used, but it can be done if the transmitting and receiving equipment operate through several independent channels. This is a well-known and widely used technique in modern telecommunication systems.

The two circuits referred to above are as follows:

a) a simple system based on amplitude modulation, with two separate channels;

b) a system with eight channels employing pulse modulation. Combined with a system of amplitude modulation, this could easily be extended to three times the number of channels; this has not been done, however, as eight channels is ample for the present purpose.

Fig. 1 shows the two radio-controlled model vessels during a demonstration. The vessel on the left is the smaller one with the simple amplitude-modulation system, whilst the other is equipped with the pulse-modulation system. The frequency of both transmitters is 100 Mc/s; this frequency represents the highest at which the valves used give sufficient amplification, whilst at the same time it permits the use of conveniently small aerials.

The transmitters, the current consumption of which is not an important factor, are mains-operated; they radiate about 1/4 watt, this being quite enough for the object in view.

The two model vessels and their respective transmitters will now be briefly described [1]).

The actual control mechanism of the models, that is, the means by which the radio (or other) signals are translated into the various manoeuvres, will be referred to here only incidentally, to clarify the functioning of the radio sections of the equipment. In the last decade, many advances have been made in the field of electronic and electro-mechanical controls, for example, remote-control equipment used for the mass-production of radio-active substances, and electronic controls for machine tools such as lathes and milling machines [2]). In this article, however, we shall confine ourselves to a brief description of the radio side of the equipment used for the two model boats.

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[1]) For a more detailed description the reader is referred to the booklet Remote Control by Radio, by A. H. Bruinsma, published in the Popular Series of the Philips' Technical Library.

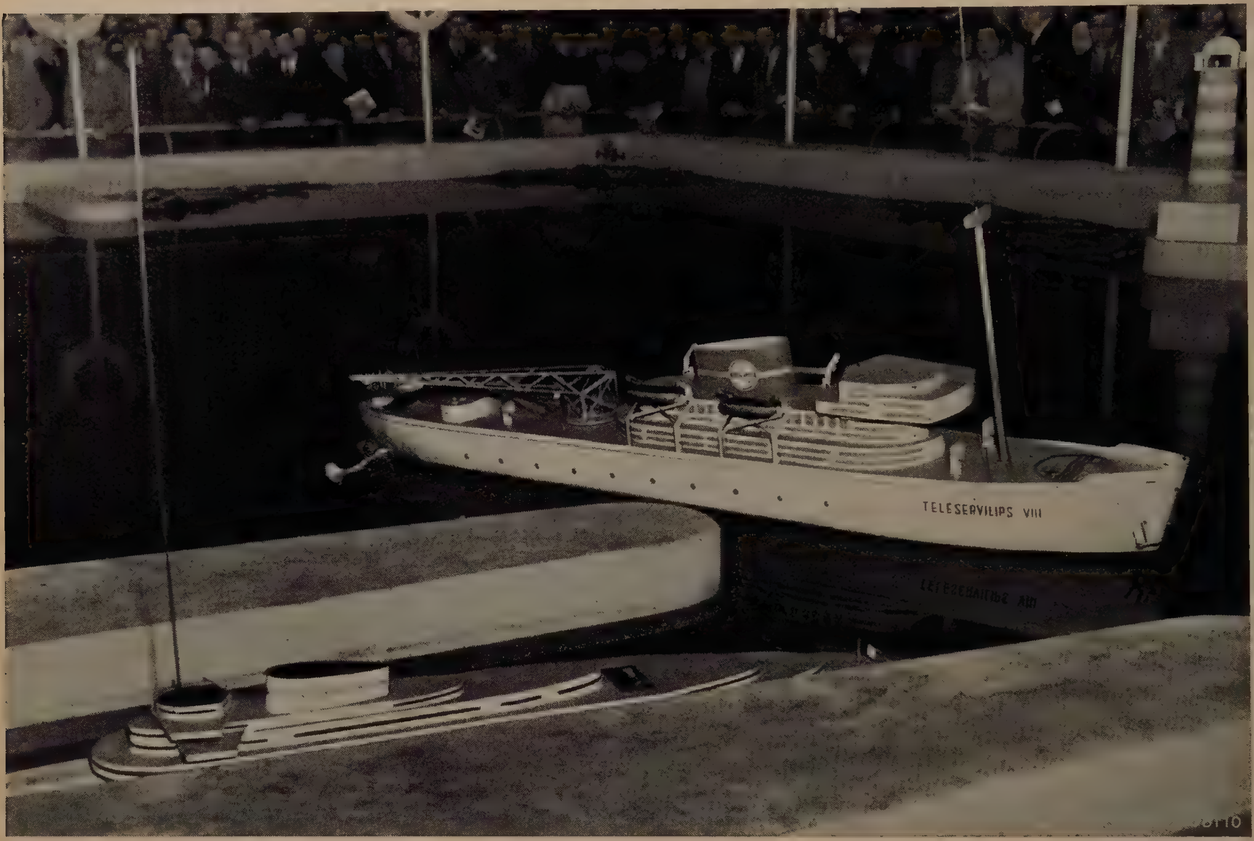

Fig. 1. The two models during a demonstration. Left, in the "harbour", is the boat equipped with the 2-channel system; right, the 8-channel model (the aircraft is just being hoisted on board).

The 2-channel A.M. system

The vessel used for demonstrating the 2-channel system of radio control is equipped with two motors, one to drive the propeller, and another for the steering.

The propulsion motor runs so long as the carrier wave is being transmitted; immediately the transmitter oscillator is cut off, it stops. Provision is made for modulating the carrier with a frequency of 50 c/s, this being effected in the output stage; the presence or absence of this modulation determines the direction of rotation of the propulsion motor, and hence the movement of the vessel — ahead or astern. In *fig. 2*, which is a block diagram of the transmitter, S_1 switches the transmitter on or off, and S_2 switches the 50 c/s modulation in or out.

In addition to the 50 c/s modulation, the carrier is modulated at 2000 c/s by the oscillator O_2, via an amplifier A. This modulation cannot be switched off at will, but is interrupted periodically by a multivibrator M at a frequency of roughly 5 c/s;

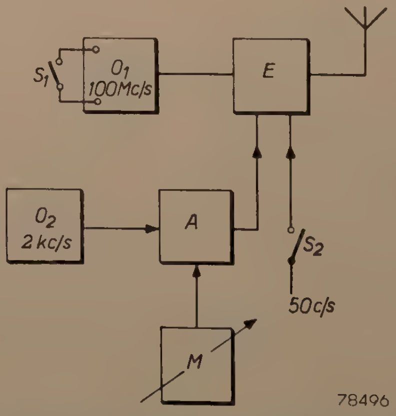

Fig. 2. Block diagram of the transmitter for the 2-channel system, employing amplitude modulation. O_1 and O_2 oscillators; E output stage; A amplifier; M multivibrator. The various "orders" are transmitted with the aid of a switch S_1 (motors on or off), the multivibrator M (steering) and the switch S_2 (direction of rotation of the screw).

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[2]) See Electronics 25, Nov. 1952, p. 172.

the timing of this modulation is variable and controls the rudder movements.

When the modulation pulse length is equal to the intervals between pulses, the steering motor, and therefore also the rudder, are stationary. Adjustment of the multivibrator to deliver modulation voltage for a period longer than the interval between pulses, causes the motor to rotate in one direction, and in the reverse direction when the modulation pulse length is shorter than the intervals between pulses. When the transmitter oscillator is switched off, thus stopping the main motor, the steering motor is also stopped. The position of the helm can be seen by a flag mounted on the stern and coupled to the rudder post.

The superheterodyne receiver in the vessel comprises seven valves (types DK 40, 2 × DL 41, DAF 91, DF 91, 2 × DL 92). In all, the filament consumption is 100 mA at 8 V; the anodes take a maximum of 25 mA at 100 V, and the total power consumed by the equipment on the vessel is therefore 3.3 W.

For the propulsion and steering, small motors of the kind fitted in "Philishave" electric razors are used, the armature and field coil being connected in series or parallel dependent on the direction of rotation[3]). With the series arrangement, these motors will work quite satisfactorily on 60 V D.C. taking a starting current of 75 mA; for the parallel connection 30 V with a starting current of 130 mA is necessary. Dependent on the load, the working current is about half to three quarters of these starting values.

The receiver and also the two motors are fed from 25 pocket-lamp batteries ($4^1/_2$ V), stowed within the vessel; this is sufficient to run the equipment for several hours without replacement of the batteries.

Fig. 3 is a photograph of the vessel with the top section removed to show the receiver, batteries and motors with their associated relays. The transmitter with its three control knobs is also shown (left, foreground). The model is 1.45 m in length and it weighs 12 kg. The receiver, the two motors and relays weigh only 1.7 kg, but the chassis and batteries account for 4 kg; it will therefore be appreciated that very much smaller dimensions would have sufficed if batteries of smaller capacity had been used.

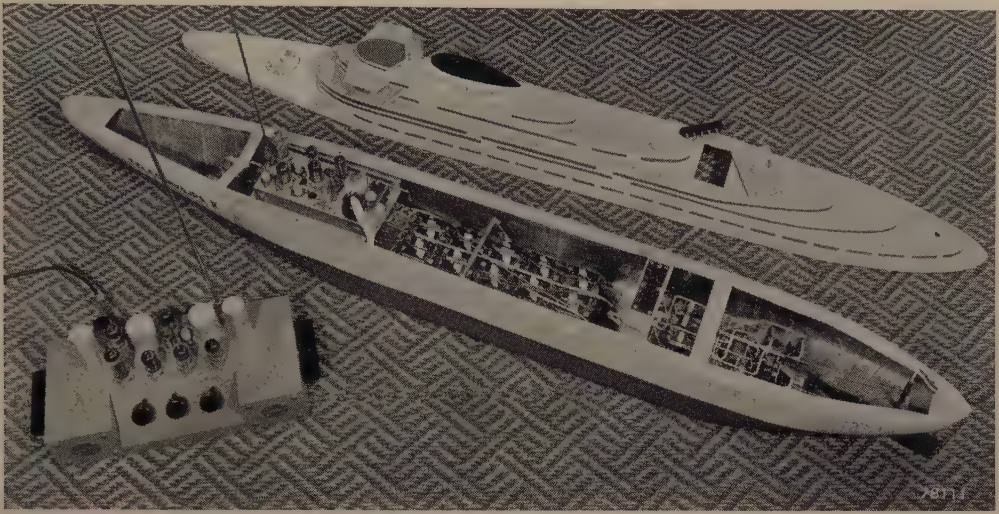

Fig. 3. Demonstration vessel for the 2-channel system with top section removed. The associated transmitter is seen in the foreground.

The 8-channel pulse modulation system

The vessel used for demonstrating the 8-channel system is a twin-screw model; in conjunction with the helm this ensures a high degree of manoeuvrability even at low speeds. Catapult equipment is included for launching a model aircraft which can subsequently be hoisted on board again with a crane. In addition, four lifeboats can be lowered and brought in again, and a loudspeaker on the foredeck provides sound in imitation of a ship's siren, or alternatively, music. The sound can be transmitted from "on shore", i.e. over one of the channels (that particular channel cannot then be included in the radio control proper).

The functions of the other 7 channels are as follows:

2. Control of port propeller

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[3]) The "Philishave" motor is actually a series-wound motor.

3. Control of starboard propeller
4. Control of rudder
5. Lowering and hauling up the lifeboats
6. Rotation of the crane
7. Operation of the crane cable
8. Operation of the catapult.

The principle of pulse modulation and the method of transmitting simultaneously independent information by this means, have already been described in this Review [4]. It is sufficient to say here that modulation of the pulse *amplitude* is employed. In the sound channel the amplitude of the pulses is continuously variable. In the other channels, which are merely switching circuits, it is only necessary for the pulse amplitude to vary between two values, viz. zero and a certain maximum, corresponding to "on" and "off". The pulseduration is 11.1 μsec and the repetition frequency is 10 kc/s.

Fig. 4 is a block diagram of the transmitter, in which *a* — *h* denote the eight pulse generators, and *i* the synchronizing pulse generator. Modulation by these pulse generators is effected in the output stage of the transmitter through channel gating valves *I* — *VIII*, and by the sync. pulse generator direct.

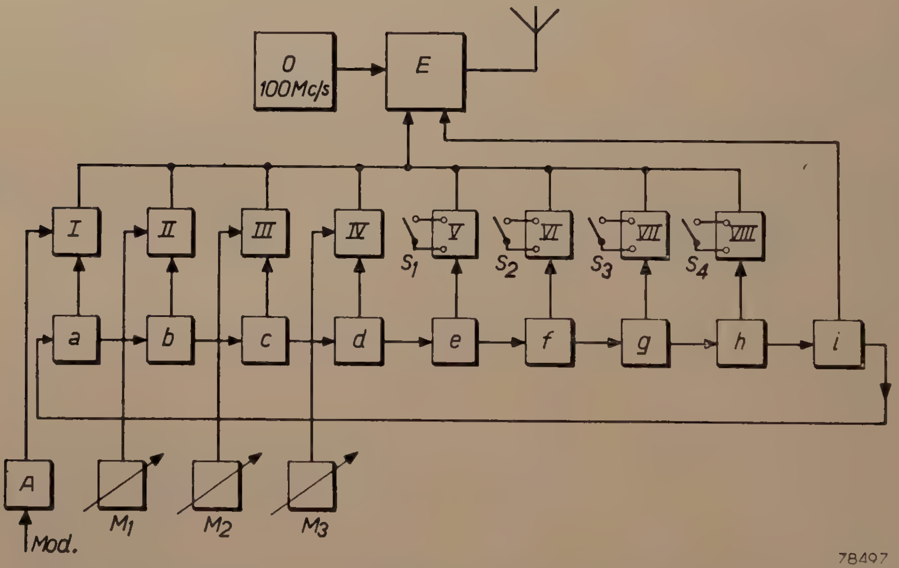

Fig. 4. Block diagram of the transmitter for the 8-channel pulse modulation system. *O* oscillator; *E* output stage; *a-h* channel pulse generators; *i* sync. pulse generator; *I-VIII* channel gating valves. The controls are effected by means of multivibrators M_1, M_2 and M_3, and switches S_1-S_4. The first channel (sound) is controlled by a modulation voltage through amplifier *A*,

An A.F. voltage is applied to the channel gating valve *I* (sound channel) through amplifier *A*. Control of the motors for the propulsion and steering is effected in the same way as in the amplitude modulation system described above. For this purpose, the channel gating valves *II*, *III* and *IV* are controlled by the multivibrators M_1, M_2 and M_3 which interrupt the train of pulses with a frequency of about 5 c/s. The direction of rotation of the motors is governed by the ratio of the pulse width to the pulse interval in the particular channel, the value of which depends on the setting of the corresponding multivibrator.

The motors controlled by the other four channels need only to be started and stopped [5], or reversed, this being achieved by switching on and off the channel gating valves *V-VIII* (switches S_1-S_4). Two channels are needed for the crane, viz. one for rotation and one for operating the cable.

The aircraft is hauled inboard by means of two permanent magnets, one of which is attached to the crane cable, the other being inside the fuselage of the aircraft; the latter is then guided into its position with the help of two guide pins; the tail is caught by a hook forming part of the catapulting equipment. The machine is launched into the air by a pair of springs engaging with the landing gear.

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[4] C. J. H. A. Staal, An installation for multiplex pulse modulation, Philips tech. Rev. **11**, 133-144, 1949.

[5] Remote reversal of the motors for the lifeboats, the crane and the crane cable is unnecessary: a tumbler switch automatically reverses the direction of rotation when the end position is reached. The motor for the catapult equipment runs only in the one direction.

This vessel is fitted with two types of motor. For the steering and crane, "Philishave" motors are used; so much power is required for the other operations that it was found necessary to employ more powerful motors. The latter employ permanent magnet stators, necessitating current only for the rotors. The "Philishave" motors are run from 8 pocket-lamp batteries, and the others from a nickel-iron battery which also feeds the receiver.

On this vessel a 40-valve receiver is used, the valves being of the types already mentioned. In spite of this large number of valves, only 2.8 W is needed for the filaments. The nickel-iron battery mentioned above delivers 24 V and has a capacity of 15 Ah; the high tension voltage, 164 V, is derived from this battery with the aid of a vibrator, and the total consumption of the receiver, which weighs 1.75 kg, is 27 W.

Fig. 5 shows the interior of the vessel for demonstrating this 8-channel system. The model is 2 m in length and weighs 60 kg. In all, the batteries (the nickel-iron and the dry batteries for the "Philishave" motors) weigh 19 kg. This boat, too, is capable of running for several hours without charging or renewal of the batteries.

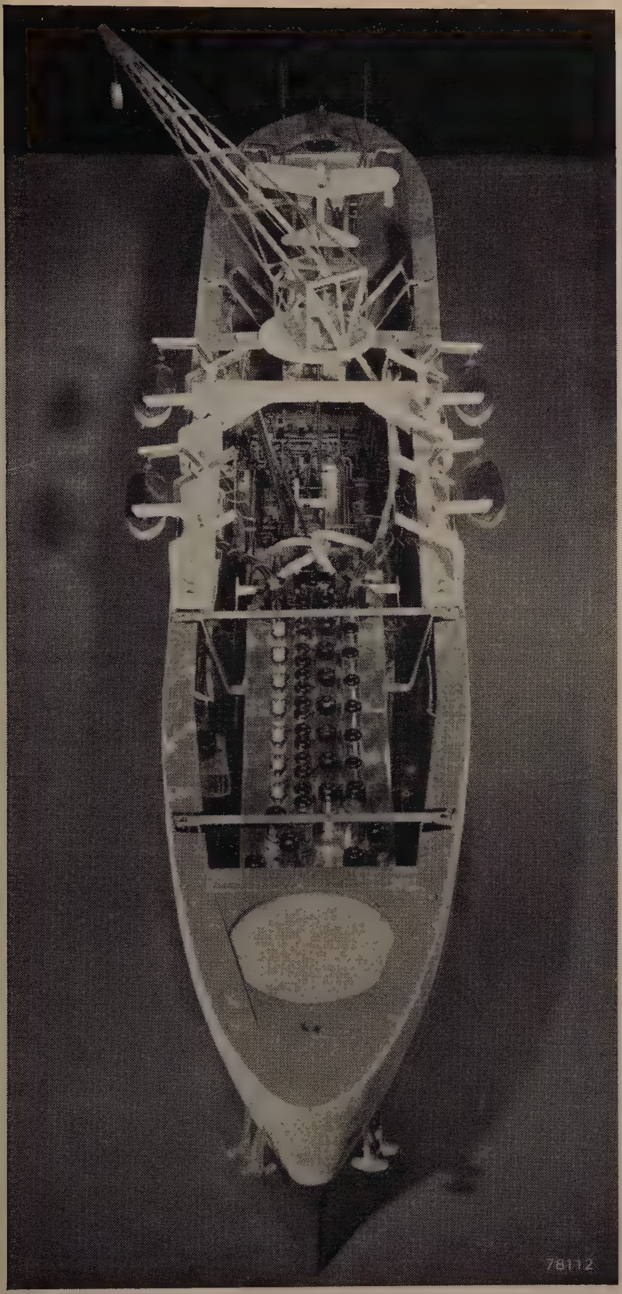

Fig. 5. View of the interior of the 8-channel radio-controlled vessel.

Summary. Two radio-controlled model boats are described; one of these, the simpler of the two, is controlled by a two-channel amplitude-modulation system. The other is a more elaborate model, capable of executing a variety of manoeuvres, and controlled by an 8-channel, pulse-modulation system. Although the smaller vessel has 7 valves and the larger one as many as 40, the amount of power required by the receivers as well as the weight of the receivers and batteries, are relatively low, owing to the use of modern low-consumption miniature battery valves.

LATTICE IMPERFECTIONS AND PLASTIC DEFORMATION IN METALS

II. BEHAVIOUR OF LATTICE IMPERFECTIONS DURING DEFORMATION

by H. G. van BUEREN.

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In a previous article the general properties of lattice imperfections such as vacancies, interstitial atoms and dislocations were discussed. With the aid of the theory as developed, it is now possible to obtain an insight into numerous phenomena of practical importance in the plastic deformation of metals, e.g. work hardening, the ageing of alloys, and variations of the electrical resistance.

Slip lines

The most important process involved in the deformation of metals is the slipping of two parts of the metallic crystal over each other. As mentioned in the previous article [1]) both the observed slip over a distance of many times the atomic spacing in a single slip plane, and the low value of the observed critical shear stress $\tau_{\rm cr}$ (compared with the theoretical value of $G/2\pi$) can be explained by introducing the idea of special kinds of lattice defects known as dislocations. These are produced in large numbers during the actual process of deformation by so-called Frank-Read sources (the emission of dislocation loops, see I).

In principle, no limit has been set for the number of dislocations that can emanate from a source, although in practice slip distances greater than about 1000 times the atomic spacing on a single slip plane are seldom observed; actually, most slip lines represent a displacement of not more than some tens to some hundreds of times the atomic spacing.

According to various workers in this field [2]) [3]), this limitation in the number of dislocation loops produced should be attributed to the stress set up by the emitted dislocations at the originating source itself; this stress is opposed to the applied stress causing the deformation and, provided it is large enough, may check the activity of the source.

The stress field around a dislocation is fairly complex. Without entering into derivations, we may say that at a distance r from a dislocation axis, stresses occur of the order of magnitude:

$$\tau \approx \frac{Gb}{2\pi r}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where G is the modulus of rigidity of the material and b the Burgers vector of the dislocation. At the centre of a dislocation loop of radius R, as produced by a Frank-Read source, this stress bears the character of a shear stress, opposed in direction to the shear stress that activates the source. The magnitude of this "back stress" set up by the dislocation loop is, in accordance with (1):

$$\tau_{\rm b} \approx \frac{Gb}{2\pi R}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If there is more than one dislocation loop, the total back stress at the source is practically equal to the sum of the back stresses that each of the dislocations would produce if they acted individually.

The critical shear stress necessary to activate a Frank-Read source is:

$$\tau_0 \approx Gb/l, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where l is the length of the source (see I, eq. (3)). As soon as the applied shear stress exceeds this value, the source commences to produce dislocation loops.

Fisher, Hart and Pry [2]) state that once a Frank-Read source has been activated, the minimum shear stress necessary for the source to continue to emit dislocation loops is about $^1/_3$rd of the value indicated by (3). If this were not so and the full shear stress τ_0 were required to maintain the activity of the source, each Frank-Read source would (assuming the applied stress remained constant) become inactive after emitting only one dislocation loop, since the back stress of that loop would in itself be enough to reduce the shear stress at the source to a value below the critical value (3). In order that the source shall actually become inactive, however, the opposing stress must attain a fairly high value, viz. of the order of τ_0.

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[1]) H. G. van Bueren, Lattice imperfections and plastic deformation in metals, I. Nature and characteristics of lattice imperfections, in particular, dislocations. Philips tech. Rev. **15**, 246-257, 1954 (No. 8/9) (hereinafter referred to as I).

[2]) J. C. Fisher, E. W. Hart and R. H. Pry. Phys. Rev. **87**, 958, 1952.

[3]) N. F. Mott, Phil. Mag. **43**, 1151, 1952 and **44**, 742, 1953.

In general, a dislocation loop emitted by a Frank-Read source does not in its entirety leave the crystal, but is — at least in part — retained in the region of the source and can thus ensure a permanent back stress. This being the case, we can interpret the limited activity of the Frank-Read source as being the result of the progressive increase in the total back stress when the number of dislocation loops increases. If the number of dislocation loops becomes so great that the total permanent back stress approximates to τ_0, the source will have become inactive. Dislocations can be halted in their progress through the crystal owing to various causes: the principal cause is the presence of other dislocations in the crystal. As mentioned in I, it is probable that a network of dislocations may be present in the undeformed crystal (of which the elements may possibly function as Frank-Read sources). Elastic stress fields will occur around such dislocations, and local stresses may attain such high values that a dislocation loop is but little affected by the applied stress that tends to move it. Secondly, when a dislocation loop intersects elements of a dislocation network, it will contain jogs which, upon further movement, will usually initiate further lattice defects, in the manner described in I. The number of newly created lattice defects increases according to the distance over which the loop progresses, and the energy needed to accomplish this can ultimately no longer be supplied by the applied stress; the dislocation loop then becomes stuck. Thirdly, a moving dislocation can combine with another dislocation moving in a different slip plane, to form a special kind of dislocation which is effectively immobile (*sessile* dislocation).

When parts of the dislocation loops emanating from each Frank-Read source become stuck in the crystal, increased deformation, resulting in the activation of more and more sources, must produce a steady increase in the total dislocation density. This is a significant conclusion of which repeated use will be made below.

Let us now return to the experimental data. The slip bands which can be seen on the surface of deformed metals under the ordinary microscope, in general contain a large number of slip lines, closely packed and extending over large distances — each representing a displacement along its slip plane equal to some hundreds of times the atomic spacing. Recent electron-microscopic studies [4]), however, have revealed that these slip bands are only special instances of a much more uniform distribution of slip lines.

The whole surface of the deformed metal crystal (those examined were aluminium, copper and silver) appears to be fairly uniformly covered with short, fine slip lines (10^{-3} cm to 10^{-2} cm in length), the so-called elementary lines, each of which corresponds to a displacement equal only to some tens of times the atomic spacing (*fig. 1*). Only here and there do the above mentioned, prominent, slip bands occur (*fig. 2*).

Fig. 1. Elementary lines on the surface of an aluminium crystal which has been stretched by a few per cent. Magnification 20,000x (Figs. 1 and 2 are taken from H. Wilsdorf and D. Kuhlmann-Wilsdorf, Z. angew. Physik 4, 341, 1952.)

Fig. 2. Surface of aluminium crystal showing slip band gradually merging into elementary structure. Magnification 15000x.

If we regard the formation of elementary lines and slip lines as characteristics inherent in the crystal as a whole, and not merely as a surface effect, we are led to the inference that Frank-Read sources in general give rise only to some few tens of dislocation loops which progress only for a short distance along their slip planes. Where such a "zone" of dislocations intersects the surface of the metal, a "step", i.e. an elementary line, occurs in the surface. The height of the step, or the displacement which the elementary line represents, is then equal to some tens of times the atomic spacing; the length of the line is of the same order as the diameter of the dislocation zone (which will in part still exist within the crystal).

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[4]) D. Kuhlmann-Wilsdorf and H. Wilsdorf, Acta Metallurgica 1, 394, 1953.

Sources lying some distance below the surface of the crystal will not in general produce slip lines. According to the above ideas, such sources will be surrounded by a number of dislocation loops running wholly within the crystal. Calculations on the behaviour of Frank-Read sources in a crystal support this conclusion [5]). The pronounced, extended slip lines are to be regarded as more or less accidental. Apparently, some favourably placed Frank-Read sources are capable of emitting a much greater number of dislocation loops than are the majority of sources. From the observed fact that the stronger slip lines often occur in groups (slip bands), it is probable that zones of a certain size may exist in the crystal which offer very little obstruction to the movement of dislocation loops or, alternatively, that the formation of an abnormally large number of loops in a single slip plane tends to promote the evolution of equally large numbers of loops in neighbouring slip planes. With regard to the occurrence of slip bands and to the effect of temperature on their structure (which although not pronounced is nevertheless present), no satisfactory explanation has yet been proposed.

According to the foregoing, the observed low critical shear stress of metals is entirely due to the presence of many sources of dislocations, e.g. Frank-Read sources. It is to be expected that, in crystals of such small dimensions that the probability of existence of a source is low, the critical shear stress will be much higher than in larger crystals, and may be expected to approximate to the theoretical value $G/2\pi$. Quite by chance, such small single crystals have become available. It was observed [6]) that under certain atmospheric conditions filaments or "whiskers" appear on the surface of several metals, of a thickness of about 10^{-4} cm. Such whiskers probably contain only one or two dislocations. Experiments have shown [7]) that these whiskers can be subjected to very considerable elastic deformation, without plastic deformation setting in. In the case of tin, a deformation corresponding to a shear stress of the order of several tens of kilograms per mm² has to be applied to these whiskers to produce plastic deformation, whereas larger crystals are plastically deformed at stresses of the order of only 0.1 kg/mm² (The theoretical shear stress $G/2\pi$ of tin crystals is about 200 kg/mm².)

Work hardening

A result of the above-mentioned increase in the number of dislocations in a metal, due to obstruction of the dislocation loops emanating from a Frank-Read source, is that as the deformation progresses, so the stress required to continue deformation increases; i.e. work hardening occurs. The quantitative effect of the premise which relates work hardening to interaction between dislocations, is not easily demonstrated, owing (amongst other things) to the uncertainty that exists as to the manner in which the dislocations are distributed through the crystal, i.e. uncertainty as to the structure of a deformed crystal.

Interaction between dislocations begins to be of importance when the forces between them are, on the average, of the same order of magnitude as the forces resulting from the applied stress in the metal. Calculation has shown that this happens when the average distance between one dislocation and another is about 10^{-4} cm or less; in other words, when the dislocation density, defined as the total length of the dislocation lines within 1 cm³ of the metal, is 10^{8} cm^{-2}, or more.

This conclusion can be reached by the following schematic reasoning. Let us imagine two parallel dislocations of Burgers vectors *b*, separated by a distance *d*. The stresses occurring at dislocation *2* in consequence of the presence of dislocation *1* are, according to expression (1), of the order of magnitude

$$\tau \approx \frac{Gb}{2\pi d}.$$

The observed critical shear stress of a metal, that is, the theoretical shear stress required to activate a Frank-Read source, is given in (I) as:

$$\tau_{\mathrm{cr}} \approx \frac{Gb}{l},$$

where *l*, the length of the source, is usually found to be of the order of several times 10^{-4} cm. If, during the deformation process, the average distance *d* between dislocations approaches the value $l/2\pi$, i.e. about 10^{-4} cm, the mean force acting between the dislocations becomes of the same order of magnitude as that resulting from the applied stress. The interaction thus assumes importance when the average spacing of the dislocations is roughly 10^{-4} cm.

If the deformation, and hence also the dislocation density be increased, the average distance between the dislocations is reduced roughly in proportion to the square root of the density; accordingly, the force necessary to accomplish further deformation, i.e. further movement of the dislocations along each other, increases approximately in direct proportion to the root of the dislocation density.

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[5]) H. G. van Bueren, Acta Metallurgica **1**, 464, 1953.
[6]) K. G. Compton, A. Mendizza and S. M. Arnold. Corrosion, **7** 327, 1951.
[7]) C. Herring and J. V. Galt. Phys. Rev. **85**, 1061, 1952.

Examination of metals by X-ray diffraction has yielded some information regarding the density of dislocations in an undistorted metal crystal: this lies somewhere between 10^7 and 10^8 cm^{-2}. In severely deformed materials, dislocation densities of 10^{10} to 10^{12} cm^{-2} are often found [8]). These figures are only rough estimates, and exact values must await future determinations; however, they have received approximate support, for example, from measurements of the internal damping in metals and by examination of the crystal boundaries.

The dislocation densities mentioned agree well with those which can be derived (along the lines of the above simple calculation) from the observed strain hardening in highly deformed materials, where shear stresses of 10 to 100 times the original value are required to achieve further plastic deformation.

Regarding the relationship between the stress σ and the deformation ε, i.e. the form of the work-hardening curve, entirely satisfactory agreement between theory and observed results has not yet been found. If it is assumed that dislocations are distributed uniformly throughout the deformed crystal — which is an assumption that cannot easily be reconciled with the mechanism of formation of dislocation from Frank-Read sources — an expression of the following form is obtained:

$$\sigma \propto \varepsilon^{1/2}. \quad \ldots\ldots\ldots \quad (4)$$

Careful experiments have shown that in hexagonal metals such as magnesium, zinc and cadmium, which usually exhibit slip only along the basal planes, and also in cubic metals such as copper, gold and aluminium, when only one slip system is active, the strain hardening characteristic is practically linear instead of having the anticipated parabolic form of (4); it is also found that the observed increase in the critical shear stress during deformation is much smaller than would be compatible with the above.

By contrast, when several slip systems are involved simultaneously in the deformation — as almost invariably occurs in cubic metals — a parabolic strain-hardening curve (*fig. 3*) is obtained which agrees reasonably closely with the simple formula (4).

It is probable that the difference between these two cases is that with only one slip system there is little intersection of dislocations, whereas when multiple slip occurs, there is a great deal of intersection, as a result of which new lattice defects are formed. Qualitatively, this would explain the greater strain hardening. The theoretical considerations outlined above would then no longer be valid; it will not be possible to find a way out of this difficulty until more is known about the structure of deformed crystals.

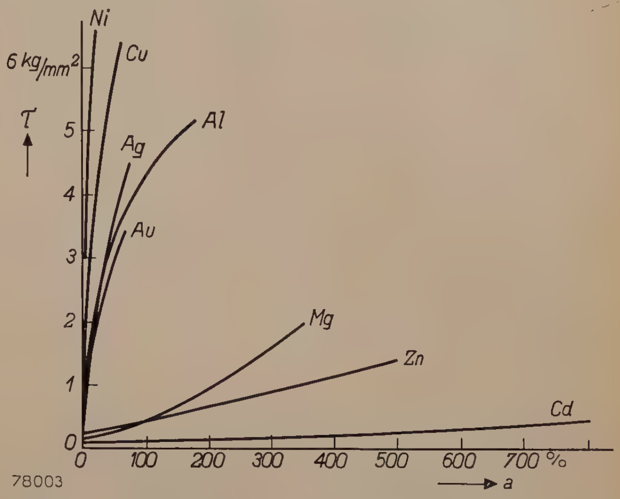

Fig. 3. Work hardening curves of hexagonal and cubic metal single crystals. The curves represent the shear stress τ as a function of the shear a. Cubic metals (Cu, Ag, Ni etc.) exhibit much more strain hardening than the hexagonal (Mg, Zn etc.); moreover, the strain hardening in cubic metals shows an almost parabolic curve, in contrast with an almost linear relationship in hexagonal metals (taken from G. Masing, Lehrbuch der allgemeinen Metallkunde, Springer, Berlin 1950, p. 362.)

Deformation bands, polygonization and recovery

Both microscopic and X-ray diffraction studies have given indications of the presence of obstacles to the movement of dislocations. Apart from slip lines, whether concentrated as slip bands or not, other formations are observed on the surface of deformed metals, which have been given the collective name of deformation bands. An example is shown in *fig. 4*. In the neighbourhood of

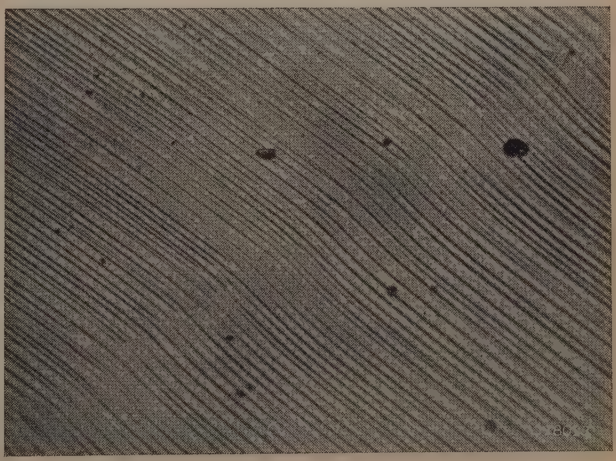

Fig. 4. Deformation band on the surface of an aluminium crystal with 20% extension. (Magnification 250x). Note the curvature of the slip lines. (Figs. 4, 6 and 8 are taken from R. W. Cahn, J. Inst. Metals **79**, 129, 1951.)

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[8]) See e.g. A. H. Cottrell, Dislocations and plastic flow in crystals, Oxford University Press, 1953, pp. 100 and 153.

such bands, the pattern of the slip lines intersecting the bands is curved, thus indicating curvature of the lattice planes. Such curvature can be the outcome of the presence of an excess of dislocations of one sign. A single edge dislocation necessarily produces some curvature of the crystal lattice, since the number of lattice planes on either side of the slip plane differs, but this curvature is too slight to be perceptible. It is different, however, when dislocations of the same sign pile up somewhere within the crystal, as for example when the successive loops emanating from a Frank-Read source become stuck. The number of lattice planes on either side of the slip plane then differs considerably, and a perceptible curvature is produced. The present conception of a deformation band is illustrated diagrammatically in *fig. 5*. Activated by a shear stress, a number of Frank-Read sources form dislocation loops of which only the cross section perpendicular to the purely edge portions are shown. All dislocations on one side of a particular source have the same sign, and those originating from the sources shown on the left-hand side of the figure (and which will have moved to the right) differ in sign from the dislocations arising from the sources on the right-hand side. In the zone where the dislocations meet, their movement becomes restricted and the dislocations pile up against one another, as illustrated in fig. 5*b*. This figure also shows the curvature in the slip planes resulting from this congestion; this curvature corresponds to that of the slip planes depicted in fig. 4.

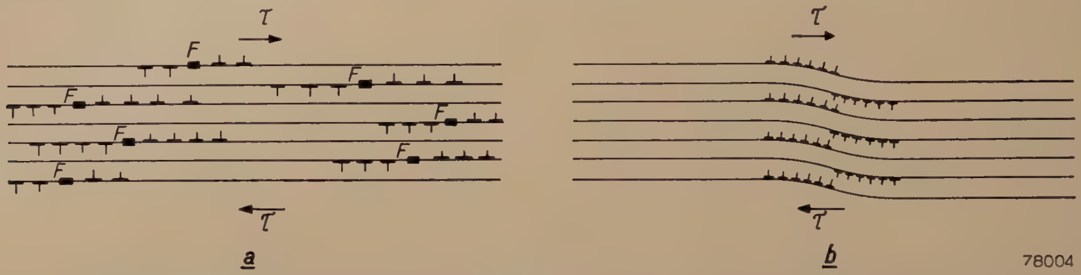

Fig. 5. *a*) When a shear stress τ is applied to a crystal, numerous Frank-Read sources *F* are activated, which then produce dislocation loops. The symbols $\perp$ and $\top$ in the figure represent the cross-sections of the edge portions of these dislocation loops in the plane of the drawing. The horizontal line shows the orientation of the slip plane, and the vertical line that of the extra atomic half-plane. *b*) With continued loading, dislocations of like sign pile up in a number of slip planes, resulting in curvature of these planes. The configuration depicted corresponds to a deformation band. (Figs. 5*b* and 7 are taken from the book of A.H. Cottrell; see reference [8])).

Such congestions of dislocations represent high concentrations of energy. Considerable stresses will occur around the deformation band, in consequence of which nearby dislocations in other slip systems will commence to move. If these dislocations reach the slip planes of the deformation band, they may be blocked by the dislocations already there. It has been shown [9]) that a very effective obstacle to the movement of the original dislocations can thus be formed in cubic metal crystals. According to Mott [3]) this process is responsible for the fact that the dislocations in the deformation band do not return when the applied stress is removed. The congestion can be eliminated only by movement of the dislocations out of their slip planes; such "climbing" movements are non-conservative, however (see I), and will occur with a reasonable frequency only at a sufficiently high temperature (several hundred degrees centigrade). In metals which have been deformed and subsequently annealed, the deformation bands do actually appear to have undergone a change, in the manner shown in *fig. 6*. The slip planes intersecting the band are now no longer curved, but are sharply kinked.

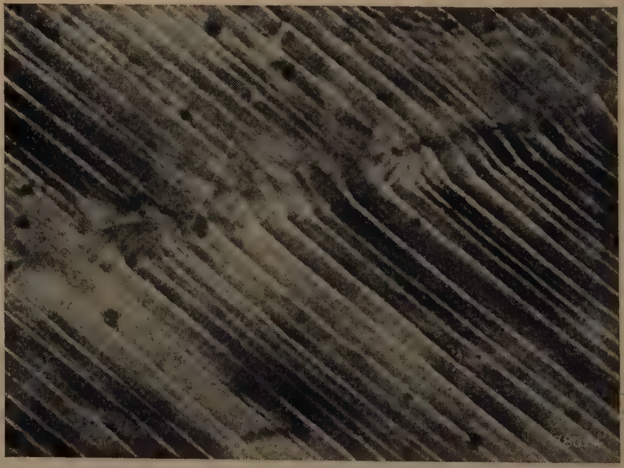

Fig. 6. Polygonized deformation band on the surface of an aluminium crystal elongated 31% and annealed for 1 hour at 450 °C after stretching. Magnification approx. 200x.

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[9]) W. M. Lomer, Phil. Mag. **42**, 1327, 1951; A. H. Cottrell, Phil. Mag. **43**, 645, 1952.

This can be explained by assuming that the climbing movement of the dislocations out of the original deformation band produces a configuration as shown in *fig. 7*. This configuration represents much less energy than the original one, because the extra half-plane of each dislocation now merges into the more loosely packed half of the next dislocation.

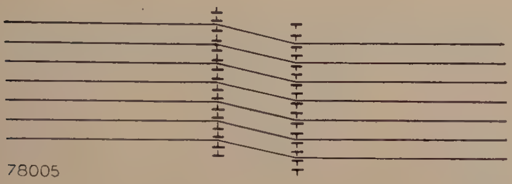


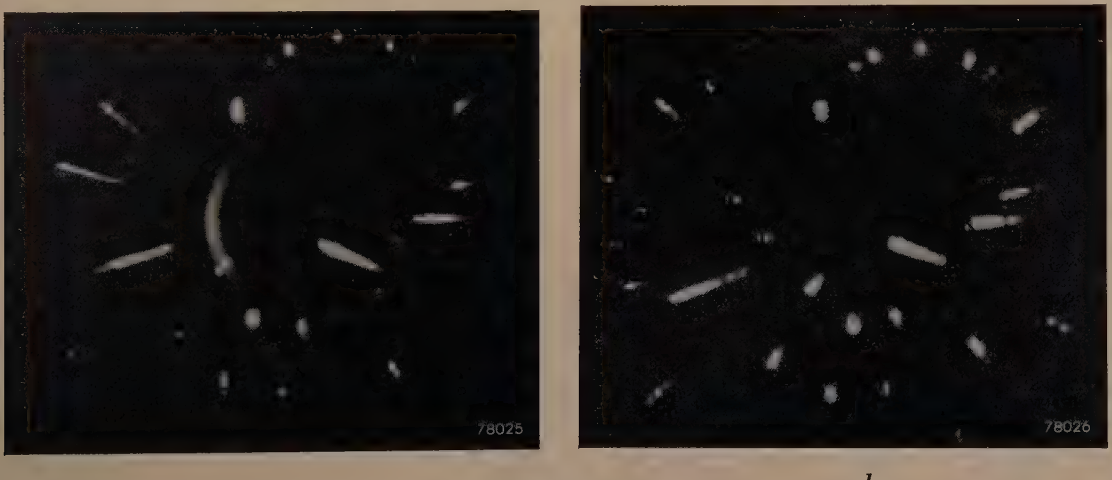
Fig. 7. At sufficiently high temperatures, the dislocations in a deformation band such as that shown in fig. 5*b* may move out of their slip planes and assume positions of lower potential energy. The result is a polygonized deformation band.

This re-grouping of the dislocations into configurations which bear the characteristics of crystal boundaries (the dislocations form divisions which separate two zones of different orientation) has been called *polygonization*. Since the stresses in the lattice are in this case considerably reduced, the mobility of the dislocations, and therefore also the susceptibility of the crystal to deformation, are greater; the work hardening is thus to a large extent eliminated. This is one of the most important causes of the well-known phenomenon of *recovery*.

In most metals recovery takes place during annealing at 400—500 °C; at higher temperatures recrystallization occurs, and here we have to assume that the lattice defects produced by plastic deformation almost entirely disappear, since the properties of a recrystallized metal are nearly enough the same as those of the original, undeformed metal.

Polygonization is also revealed by X-ray diffraction examination which was, in fact, the medium through which this phenomenon was first discovered. The diffraction pattern of an undeformed metal consists of a number of sharply defined points, which become elongated by deformation to form lines, or so-called asterisms, most of which are oriented radially (*fig. 8a*). After annealing at the recovery temperature, the nature of these asterisms is found to have undergone a change, in that the continuous diffraction streaks have broken up into discrete spots (fig. 8*b*). This modification in the diffraction pattern suggests the occurrence of a substructure in the crystal, i.e. numerous crystal elements of slightly differing orientations. This substructure can be identified with that which occurs after polygonization, that is after the formation of a number of polygonization boundaries.

We will now break off our discussion of present-day conceptions of the behaviour of dislocations, and turn our attention to certain other effects in which the lattice defects produced by plastic deformation play a part.



a *b*

Fig. 8. *a*) Transmission Laue photograph of aluminium crystal elongated by 7%. The deformation is revealed by the elongated diffraction streaks (asterisms). *b*) The same crystal after 36 hours annealing at 590 °C. The asterisms are now broken up into discrete spots.

Effects of lattice imperfections in alloys

The effect of lattice imperfections in alloys is threefold: such defects facilitate diffusion of both the foreign atoms and the atoms of the host-metal; they promote the formation of nuclei of a new phase and they can also function as "capture centres" for foreign atoms. As a result of the first two of these effects, phase transitions, recrystallization, precipitation etc. are all considerably assisted by the presence of lattice defects. Plastic deformation, therefore, which is itself a source of lattice defects, must appreciably accelerate these effects. As an example, it is sufficient to mention the experiments carried out in connection with the increase of the precipitation rate of copper in aluminium, caused by cold working [10]). The precipitation rate of copper in aluminium containing 4% of copper, previously rolled to 10% of its original cross-section, is some 1000 times higher than in the undeformed metal. Microscopic examination shows that the precipitation takes place preferentially in the slip planes, i.e. in those parts of the lattice where the deformation is concentrated.

The ageing of alloys, viz. the gradual variation in hardness that occurs for example after quenching, is also influenced by the presence of lattice defects, As previously explained in this Review [11]), the quench-ageing of carbon steel, for example, is based on the precipitation of the dissolved C-atoms in the phase that is stable at lower temperatures (in this case Fe_3C). In order to accomplish the precipitation, the C atoms must diffuse throughout the lattice. It is therefore evident that the precipitation rate, i.e. the ageing rate, increases steeply when the quenched metal is deformed, e.g. rolled [10]) [12]).

It is interesting to note that the deformation does not appear to affect the precipitation activating energy, but merely multiplies the precipitation rate by a factor that is independent of temperature. It seems that the number of sites to which a dissolved atom can jump is increased, but that the energy necessary for such a jump remains the same. The effect is probably a result of the large number of vacancies created during the deformation process (see I).

The fact that lattice defects can also function as capture centres for foreign atoms is borne out by the effect known as strain ageing. When a metal containing foreign atoms in solution is deformed, it will subsequently exhibit a gradual variation in hardness. The explanation offered by Cottrell and Bilby [13]) has already been discussed in a previous article [14]); it is founded on a trapping of the solute atoms in dislocations which are produced in large numbers during the process of deformation. The best example of strain ageing is found in α-iron containing carbon or nitrogen; the C and N atoms are located at interstitial sites, but they are slightly too large for the available space and therefore show a tendency to diffuse towards the dilated lattice zones in the region of edge dislocations (or dislocations preponderantly of the "edge" type). Here they are trapped, but the dislocation is then blocked, for, in order to move further, it must either take the atom with it or break away from it. Both processes clearly hinder the motion of the dislocation, and the metal as a whole becomes harder. Intimately connected with this phenomenon is the occurrence of the sharp yield point in iron containing C or N. According to the theory, the yield point corresponds to the stress needed to break away the dislocations from their locking points, viz. the trapped C or N atoms.

It is difficult to calculate exactly the ageing rate as a function of the concentration q of the foreign atoms and of the diffusion coefficient D of these atoms in the parent metal. The difficulties are partly due to the peculiar stress field surrounding the dislocation, and partly to the fact that the atoms in solution normally show a tendency not only to diffuse towards the dislocations, but also to form precipitates of the phase which is most stable at low temperatures. In the original theory of Cottrell and Bilby, the last-mentioned effect is disregarded. It has been shown by Fast, however, from experiments based on the internal damping in iron containing either carbon or nitrogen [14]), that the equilibrium concentration of free C or N atoms at ordinary temperatures is so small that these atoms can produce little or no strain ageing. We are thus forced to conclude that the C or N atoms responsible for blocking the dislocations are either present in much higher concentrations than correspond to equilibrium, or that they are produced by the carbide or nitride precipitates present. In the latter event, it can be demonstrated that if the precipitate occurs in the metal in a finely dispersed state, the rate of ageing is determined as a first approximation by the product Dq. This could explain why nitrogen in α-iron results in much more rapid ageing than carbon, at the same temperature.

A phenomenon for which a really satisfactory explanation has not yet been given but which is probably largely determined by the behaviour of dislocations and other lattice defects, is that of creep. This is the slowly increasing plastic deformation of a loaded material that occurs after the instantaneous value indicated by the stress-strain curve has been reached. It is possible to make a distinction between various stages of creep: the most important stage in practice is the steady-state creep which occurs only at elevated temperatures. A special article on the subject of creep is shortly to appear in this Review, however, so a discussion of the mechanism or mechanisms of this effect will be deferred for the present.

In conclusion we shall turn to the question of the variation in the electrical resistance of metals when deformed, particularly at low temperatures.

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[10]) M. L. V. Gayler, J. Inst. Metals 72, 243, 1943.
[11]) J. D. Fast, Philips tech. Rev. 13, 165-171, 1951.
[12]) G. C. Smith, Progess in Metal Physics 1, 163-234, 1949.
[13]) A. H. Cottrell, Progress in Metal Physics 1, 77, 1949. B. A. Bilby, Proc. Phys. Soc. A 63, 191, 1950.
[14]) J. D. Fast, Strain ageing in iron and steel, Philips tech. Rev. 14, 60-67, 1952.

Variation in resistivity due to plastic deformation

Metals possess electrical resistance because the electrons, which as carriers of the current follow a mean path in the direction of the applied electric field, are scattered by lattice defects. A metal with a perfect lattice would have no electrical resistance; hence the resistivity can be regarded as an indication of the divergence from the perfect lattice structure.

At ordinary temperatures, by far the greater part of the resistance is produced by scattering due to thermal vibrations of the lattice; in alloys, scattering is also produced by the alloying atoms. At low temperatures (in the region of the boiling point of hydrogen or lower), the relative effect of lattice vibrations is very slight, and the resistivity of pure metals accordingly drops sharply below that of alloys.

It appears that the plastic deformation of a metal can increase the resistivity to a fairly considerable extent. At ordinary temperatures, the relative increase in resistivity of a heavily worked metal usually amounts to a few per cent; the high melting-point metals such as tungsten and molybdenum are exceptions as their resistivity can rise 10-50 per cent. This increase can be attributed to the large number of lattice defects produced by plastic deformation.

To a first approximation, the various contributions towards the total resistivity arising from one cause or another are additive (Matthiesen's law), so it may be anticipated that the relative variation in resistivity due to plastic deformation at low temperatures, where the effect of lattice vibrations is only slight, will be greater than at ordinary temperatures. Investigation is therefore best carried out at low temperature.

Measurements on metal wires stretched a few percent at the temperature of liquid air 15) show that the relative increase $\Delta\varrho/\varrho$ of the resistivity at this temperature is of the same order of magnitude as the relative variation in the length $\Delta l/l$ of the wire. The results of some of these measurements are shown graphically in *fig. 9*.

The relationship between the increase in resistivity and the extension is not linear; analysis of the curves shows that it may be approximately represented by:

$$\frac{\Delta\varrho}{\varrho} = a\left(\frac{\Delta l}{l}\right)^n, \quad \ldots\ldots\ldots \quad (5)$$

where a is a proportionality constant which is of the order of unity at the temperature of liquid air, and n is generally about 3/2.

Of the various kinds of lattice defects that can be held responsible for the increase in resistivity, the first that come to mind are, of course, dislocations. There are indications, however, that dislocations are responsible for only a small part of the total increase. It follows from various experiments, and is also acceptable from current theoretical points of view, that the dislocation density in a lightly deformed metal (with which we are here concerned) will be at most 10^{10} cm^{-2} (see above). The scattering power of a dislocation can be calculated approximately 16), and it is then seen that, to explain the increase in resistivity observed in the above-mentioned experiments, a much greater dislocation density is required, viz. from 10^{11} to 10^{12} cm^{-2}.

Dislocations thus appear to be responsible only for a minor part of the observed variation in resistivity. On the other hand, vacancies and interstitial atoms produced by the plastic deformation of a metal can easily cause the observed effects. As mentioned before, such lattice defects occur in large numbers as a consequence of intersection among the dislocations during their progress through the crystal lattice. Jogs are thus produced which leave a trail of vacancies or interstitial atoms in their wake as they move forward. Assuming that the dislocations are almost all generated by Frank-Read sources and that the jogs are formed by the intersection of dislocation loops with the existing network of dislocations, an extension of 10% will yield a concentration of vacancies of about 10^{19} per cm^3.17)

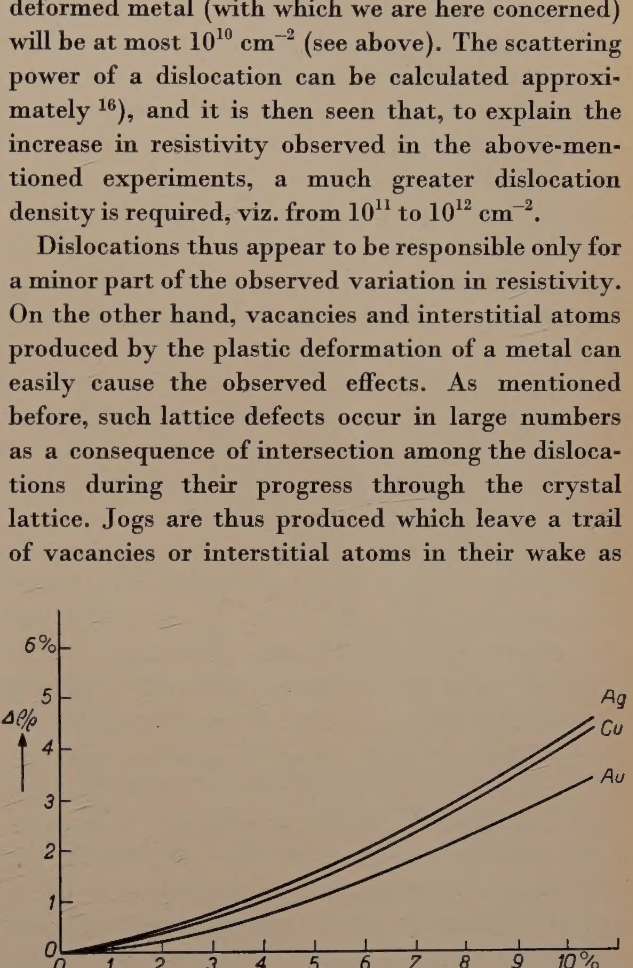

Fig. 9. Relative variation $\Delta\varrho/\varrho$ of the resistivity of silver, copper and gold, due to plastic elongation, plotted against relative variation in length $\Delta l/l$ of the wire, at the temperature of liquid air (unpublished work of J. H. Manintveld, Delft).

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15) J. Molenaar and W. H. Aarts, Nature, **166**, 690, 1950; M. J. Druyvestein and J. A. Manintveld, Nature **168**, 868, 1951.

16) D. L. Dexter. Phys. Rev. **85**, 936, 1952.

17) H. G. van Bueren, Acta Metallurgica **1**, 607, 1953.

The scattering power of vacancies and interstitial atoms for electrons can also be computed[18]; the results obtained by various workers vary to some extent, but on average it may be taken that a concentration of such lattice faults of 10^{18} to $10^{19}/\text{cm}^3$ will be sufficient to explain the observed variations in resistivity.

The deformation ε, and the number of jogs formed, are proportional to the total area covered by the loops emitted by a Frank-Read source, i.e. to the square of the mean radius of the loop. The number of lattice defects left in the trail of the jogs will be proportional to the number of jogs and to the distance progressed by a jog, that is, the mean radius of the loops or, in total, to the 3rd power of this radius. The extent of the scattering of the electrons and hence the increase in resistivity can be said to be proportional to the number of new lattice defects per cm³; hence the relationship between the increase in resistivity and the deformation can be expressed in the following form:

$$\Delta\varrho \sim \varepsilon^{3/2},$$

in agreement with the observed relationship (5).

If the material, deformed at the temperature of liquid air, is subsequently raised to a higher temperature, some of the extra resistivity is found to disappear. (This refers to the absolute value $\Delta\varrho$ of the extra resistivity; the relative value of the extra resistivity $\Delta\varrho/\varrho$ drops, of course, since the effect of the lattice vibrations (which determine ϱ) in relation to that of the other lattice defects (which determine $\Delta\varrho$) increases with temperature.) A close study of this resistivity recovery[19] has proved that more than one recovery process is involved, each of which depends on the temperature in accordance with an exponential law in which an activation energy appears. A distinction is made nowadays between three different recovery processes (*fig. 10*). The first of these takes place (certainly, at least, in silver, copper and gold) at temperatures in the region of —100 °C; this is not characterised by a clearly-defined activation energy, but by a range of energies. During this recovery, the extra resistivity drops by 10-20 % or more. The second process occurs (in the metals mentioned) within the range of ordinary temperatures; in this case the value of the activation energy can be much more closely determined. When this recovery has taken place, about half of the extra resistivity is still left. The third recovery process sets in at several hundred degrees centigrade and is intimately connected with the mechanical recovery mentioned in a previous section. By contrast, the two first mentioned processes in the recovery of the resistivity are accompanied — if at all — by hardly any variation in the mechanical properties. This is a further argument in support of the assertion that dislocations are only in part responsible for the extra resistivity.

The recovery processes are undoubtedly closely linked with the diffusion of the vacancies and interstitial atoms to sites where they have less influence, or none at all, on the resistivity. The first of the recovery processes mentioned is at present regarded as the result of the recombination of vacancies and interstitial atoms, and the association and dissociation of groups of these defects. Regarding the quantitative effect of these processes we are still in the dark. It is probable, in view of the relatively broad band of activation energies, that a number of processes take place simultaneously. Very probably too, the second process can be attributed to the diffusion of vacancies to the metal surface, to grain boundaries and to dislocations where they are partly eliminated and partly blocked, whereby their influence on the resistivity is reduced. The activation energy for diffusion of vacancies tallies well with that involved in the second recovery process. The progress of the dislocations is to some extent hindered by the blocking effect resulting from the trapped vacancies. This agrees with recent findings[20], according to which the second

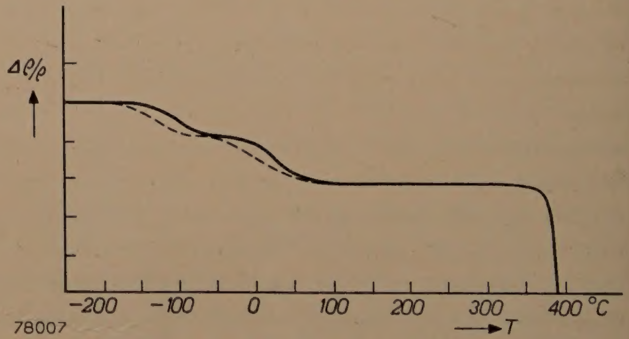

Fig. 10. Recovery of the extra resistivity of a metal produced by deformation at —180 °C after heating at higher temperature. After stretching the (Cu) wire, the temperature is increased to —150 °C for 15 minutes; the wire is then cooled again to liquid air temperature (180 °C) and the resistivity again measured; other parts of the wire are annealed at —130 °C for 15 min, the resistivity being again measured at the temperature of liquid air, and so on. The form of the curve is very dependent on the time during which the wires are maintained at the various temperatures; the dotted part of the curve shows the variation in resistivity for annealing periods of 45 min. From these curves the activation energy of the various recovery processes can be derived. (The curve is due to J. A. Manintveld [19]), except that the part above ordinary temperatures is purely diagrammatic.)

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[18] The most recent computation is that of P. Jongenburger, Phys. Rev. **90**, 710, 1953.

[19] J. A. Manintveld, Nature, **169**, 623, 1952.

[20] T. H. Blewitt, Phys. Rev. **91**, 1115, 1953.

recovery process is accompanied by a slight increase in the mechanical hardness. The third process is closely related to the movement of dislocations during mechanical recovery (polygonization), whereby, according to Mott [3]), a large number of vacancies or interstitial atoms disappear, (during the climbing movement of the dislocations), and also the effect of the dislocations on the resistivity is reduced, probably as a consequence of their more favourable arrangement in the lattice.

In this and the previous article, an attempt has been made to present a picture, albeit incomplete, of the formation of lattice defects and their effects in plastic deformation. As this field has been the subject of experimental and theoretical research only a short time, it is not surprising that this review contains so many references to the inadequacy or uncertainty of the theoretical interpretations. Because of this fallability, moreover, the manner in which the views of other workers are presented is unavoidably biassed by the views of the writer. However, there can be no doubt that lattice imperfections constitute a very important factor in the present field of investigation, and that a study of their effects on a wide range of phenomena will ultimately lead to a concise picture of what is now largely a detached collection of fact and hypothesis.

Summary. Following an introductory article, the plastic deformation of metals by the mechanism of slip is discussed with reference to microscopic observations. The following points are dealt with: the various kinds of slip lines visible on the surface of deformed metals, the work hardening resulting from the stress fields round the dislocations, and deformation bands which constitute experimental evidence of the blocking of dislocation movements. Polygonization and recovery are briefly discussed, as well as some phenomena related to lattice defects in alloys, viz. ageing phenomena. In conclusion, some comments are made on the variation in resistivity due to plastic deformation, and its possible theoretical explanation.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an arterisk * can be obtained free of charge upon application to the administration of the Philips Research Laboratory, Eindhoven, Netherlands.

2040: F. A. Kröger: The location of the activator in fluorescent ZnS-Cu (J. chem. Physics **20**, 345-346, 1952, No. 2).

It is argued, — against the opinion of others — that in green-fluorescent ZnS-Cu the activator ion (Cu^+) is located at a normal cation site. Charge compensation is effected either by Cl^- on a normal anion site or by replacing two Zn^{2+} ions by a monovalent Cu^+ ion and a trivalent ion. The blue fluorescence of ZnS-Cu-Cl with high copper concentration is attributed to a monovalent complex, $Cu_2{}^+$. At high temperatures these preparations show a green fluorescence. Centres containing more than two Cu atoms act as "killers", influencing the temperature at which the blue fluorescence is suppressed in favour of the green. See Nos. **1931** and **1902**.

2041: B. H. Schultz: Approximative formulae in the theory of thermal regenerators (Appl. sci. Res. **A3**, 165-173, 1952, No. 3).

The application of Hausen's theory to the temperatures and efficiency of regenerators involves very laborious computations. In this article it is shown that, for some limiting cases, more simple formulae can be found with the aid of perturbation theory. The formulae are series expansions for the fluctuating temperatures and the efficiency, in terms of the reduced surface Λ and the reduced heat capacity Γ of the regenerator, for the case of $\Gamma \gg 1$ and $\Lambda \gg 1$, under balanced load conditions.

2042: I. Pelchowitch and J. J. Zaalberg van Zelst: A wide-band electrometer amplifier (Rev. sci. Instr. **23**, 73-75, 1952, No. 2).

It is shown that by appropriate feed-back methods it is possible to construct a wide-band electrometer amplifier with a stable flat response characteristic. Theoretically, the signal-to-noise ratio has been found to be most favorable in the case where the mean frequency of the amplifier is low. Some practical values of the circuit components are given.

2043: J. D. Fast: The allotropic transformation of hafnium and a tentative equilibrium diagram of the system zirconium-hafnium (J. appl. Physics **23**, 350-351, 1952, No. 3).

The temperature of the transformation in hafnium is at least 550 °C higher than the value recently reported by Dewez and is estimated in this paper as 1950 ± 100 °C. A tentative equilibrium diagram of the system zirconium-hafnium is given. From this it would appear that in the neighbourhood of 100% Hf the transition temperature is very sensitive to small admixtures of Zr.

2044: J. M. Stevels: Expériences et théories sur le facteur de puissance des verres en fonction de leur composition, III (Verres et Réfractaires **6**, 3-7, 1952, No. 1). (Experiments and theories on the power factor of glasses; in French).

French translation of **R 189.**

R 198: M. E. Wise: Dense random packing of unequal spheres (Philips Res. Rep. **7**, 321-343, 1952, No. 5).

A heap of rigid spheres has a given typical statistical distribution for their radii, and the spheres are densely packed like the grains in a powder. "Dense random packing" is defined in a new way, in terms of a probability distribution function W for tetrahedra: each tetrahedron has its vertices at the centres of four spheres of which every sphere has to touch the other three. Thus W is defined by four radii. Boundary effects are ignored. General equations for W are deduced and also one of the possible numerical solutions for one log-normal distribution of radii; this is used to obtain approximations for several of the most interesting geometrical properties of the heap. In this way, for example, the mean density and the mean number of interstices are found, and also a statistical distribution for the largest possible spheres that can go into the interstices, and one for the number of spheres touching one sphere of given radius. Finally, the system is discussed critically as a model for a real packed heap. The mathematical methods are also of interest: these include some little-known formulae of solid geometry and formulae for integrating numerically in two, three and four dimensions.

R 199: J. Bakker: Kinetics of the emulsion polymerization of styrene (Thesis, Utrecht, Philips Res. Rep. **7**, 344-400, 1952, No. 5).

The rate of polymerization of styrene in an emulsion has been measured by a dilatometric method, while at the same time the end of the incubation period has been determined by measuring the change in electrical conductivity of the emulsion. The curves representing the conversion as a function of time proved to be S-shaped. The measurements were accurate to within 5%, the error being due mainly to the difficulty in determining the moment at which the reaction begins. Up to 50% conversion, this conversion-time function could be represented by $x^{\frac{1}{2}}(1-x)^{-\frac{1}{2}} = t/t_{\frac{1}{2}}$, independently of the amounts of soap or catalyst used, when the emulsifier is potassium myristate ($x =$ degree of conversion, $t =$ time, $t_{\frac{1}{2}} =$ half-conversion time). When other soaps are used — laurate, stearate or oleate — small deviations from this formula were found. Beyond 50% conversion, the function could be represented by

$$\frac{1-\varphi}{k}\,(x-\tfrac{1}{2}) - \frac{\varphi}{k}\ln 2(1-x) + 1 = t_{\frac{1}{2}}$$

where k probably depends on the nature of the soap, but not upon the amounts of soap and catalyst; φ is characterstic of the monomer. With K-myristate as emulsifier, k was found to be 1.10 ± 0.07. This parameter is related to the number of latex particles, thus making it possible to evaluate this number. Given equal quantities of monomer and equal volumes of water, the half-time value $t_{\frac{1}{2}}$ bears a relation to the amounts of soap (S) and catalyst (R), viz $t_{\frac{1}{2}} =$ const. $(SR)^{-\frac{1}{2}}$. The moment at which the incubation period ends (t^*) appeared to be practically independent of the amounts of soap, but dependent upon the amount of catalyst as $t^* =$ const. $R^{-2/5}$ or, after correction of the experimental values of t^* on theoretical considerations, as $t^* =$ const. $R^{-3/5}$. This applies only as long as the amounts of soap used are less than 15% by by weight of the amount of monomer. When this limit is exceeded the micelles no longer disappear entirely from the solution. From considerations of the initiation theory of Smith and Ewart, another method was found for determining the number of latex particles, which, combined with the first method, provided a means of calculating the area ω_0 occupied by one molecule of soap. For K-myristate we found $\omega_0 = 35 \pm 6$ Å^2. Investigations concerning the initial stages of the reaction revealed that $t_{\frac{1}{2}}$ should depend not only upon specific properties of the soap but also upon the initial weight of monomer m_0 and upon the volume of the aqueous phase V. Experiments showed, however, that $t_{\frac{1}{2}}$ is independent of V but directly proportional to $m_0^{\frac{1}{2}}$, within the range covered by the experiments. Further experiments are required before any conclusion can be drawn as to the dependence of $t_{\frac{1}{2}}$ outside the present range. Some measurements of the degree of polymerization of the polymers obtained led to the conclusion that this is determined entirely by chain transfer, which is reconcilable with the concept of the termination reaction in the case of emulsion polymerization. In none of the experiments was any modifier used.